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CONTENTS

Page

OBITUARY.
A. RAMSAY MOON, B.A., B.C.E., M.I.Struct.E., M. Inst. W. 251*r*

A.C. Argonarc Process for Welding Aluminium: an Oscillographic Analysis of Effects of Welding Transformer Open-Circuit Voltage on Arc Re-ignition .. 252*r*

Spot Welding of Coated Mild Steel Sheet 275*r*

A. RAMSAY MOON

B.A., B.C.E., M.I.Struct.E., M.Inst.W.

With very great regret we have to announce the death of Allan Ramsay Moon the first Director of Research of the British Welding Research Association. Ramsay Moon, as everyone knew him, died at sea on 15th December from a heart attack. He was on his way back with his wife to this country from Australia and was looking forward with great excitement to his return to this land he loved so much and to meeting his old friends once again. An appreciation of Ramsay Moon and of the work he did for the Institute of Welding and the Research Association, by Sir William Larke, is given below.

The development and application of welding in engineering and metal construction generally owes much to the work, energy and ability of Mr. Ramsay Moon. His death at the comparatively early age of fifty-three has deprived us of one of the ablest and most enthusiastic pioneers in this field. Born in Australia, he graduated in Civil Engineering from the University of Melbourne. In 1924 he became interested in the application of welding in connection with the repair of one of the city's main bridges which was not strong enough to carry the increased loading of a new electric tramway. As a result of the success of this experiment a comprehensive programme of repair, by welding, of railway and highway bridges was carried out in Australia long before welding was considered for this purpose in other countries.

Realising that many of the difficulties of applying welding in engineering construction were due to a failure to appreciate the rigid monolithic nature of welded structures, as opposed to the flexible nature of riveted structures, he turned his attention to problems of new designs which would provide for the complete redistribution of stresses involved. In 1929 he supervised the construction of a structure of 1,000 tons of welded steelwork, then the largest yet built, and about the same time, he prepared a design for what was probably the first welded railway rolling stock. While he realised the importance of the metallurgical problems involved in the application of welding, and fully appreciated the work of his metallurgical colleagues and its contribution to effective welding, he never claimed a fundamental knowledge of metallurgy.

By temperament he was an individualist: an imaginative thinker in his own field with a distinguished presence and a ready, dry wit. Although personally popular, he was naturally reticent—a protection against over-sensitiveness, accentuated by his artistic temperament and high ideals.

He joined the Institute of Welding early in 1937, following an international congress on welding which had been organised in this country by seventeen major technical institutions, led by the Institution of Civil Engineers with the Iron and Steel Institute acting as convening body. The Congress of 800 delegates from 16 countries passed a series of resolutions defining the general principles of welding research policy. None of the sponsoring institutions was able to accept responsibility for the whole of the wide field of research covered. They therefore invited the Institute of Welding, then a much smaller body, to accept responsibility, promising their support. Sir Alexander Gibb, then President of the Institution of Civil Engineers, accepted the Presidency, and Ramsay Moon, having had a long and varied experience in the theory and practice of welding, was appointed to organise and direct the research. He was secretary of the Institute from 1937 to 1943 when he became Director of Research under the Welding Research Council. When the Department of Scientific and Industrial Research required the research work to be placed under a separate research association, as a condition of continuing the grant from public funds, in 1946, he became the first Director of the new British Welding Research Association.

It was due to his vision and energy that the Headquarters at Park Crescent and the Research Station at Abington were established, both at a time when the financial resources available were limited, but his faith and enthusiasm overcame all obstacles as they arose. He would admit that he was most generously supported by the industries concerned and by the membership of the Institute. Having been intimately associated with him in his work during the whole period of his connection with the Institute and the Research Association, the present writer can testify to his unswerving loyalty, high integrity and attractive personality. We have lost by his early death both a personal friend and an invaluable worker in the application of welding, so important to our economic life to-day.

W. J. L.

R.74

A.C. ARGONARC PROCESS FOR WELDING ALUMINIUM

AN OSCILLOGRAPHIC ANALYSIS OF EFFECTS OF WELDING TRANSFORMER OPEN-CIRCUIT VOLTAGE ON ARC RE-IGNITION.

Report Z/T82 of the British Electrical and Allied Industries Research Association.

By L. H. ORTON, Ph.D., F.Inst.P., and J. C. NEEDHAM, B.Sc. (Eng.)

SUMMARY

The a.c. arc in the argonarc process for welding aluminium has here been examined, using oscillographic techniques with time resolution of recording down to microseconds, and the marked differences in both the arcing and re-ignition characteristics between the straight and reverse polarity half-cycles have been analysed. In a typical welding circuit the arc re-ignition process for the reverse polarity half-cycle is shown to be complex, and, in general, there is a series of " ignition oscillations," each cycle of which lasts some 10 microseconds and is repeated some 10 to 50 times, before the arc is finally established in the half-cycle. These ignition oscillations can occur whether the arc is re-ignited by an injected spark from an h.f. spark oscillator, or by a sufficiently high open-circuit voltage alone. The re-ignition process is modified by conductivity in the arc gap around the current zero period, following the extinction of the straight polarity half-cycle.

Several stages of arc re-ignition have been recognized with increase of open-circuit voltage from a value insufficient to avoid half-cycle rectification, in spite of h.f. spark injection, to a value adequate for a self-maintaining arc.

The bearing of these phenomena on the open-circuit voltage required to re-ignite the arc has been studied and voltages established for maintaining the arc both with and without h.f. spark injection, with and without a large series capacitor, on commercially pure aluminium and an aluminium-5% magnesium alloy, using a commercial leaky-reactance type welding transformer. It is shown that the spark injector permits a reduction of about 60 volts in open-circuit voltage from that required for a self-maintaining arc, and the addition of a series capacitor, about 15 volts reduction. The marked effects of the surface condition and material of the work plate on the required voltage have also been demonstrated. The data provide a probable explanation of the apparent discrepancy in the open-circuit voltages extant in literature.

Under optimum conditions the argonarc was successfully maintained on an Al-5% Mg plate at an open-circuit voltage as low as 45 volts r.m.s.

1. INTRODUCTION

In the a.c. argonarc process for welding aluminium, for reasons of economy and safety[1], it is desirable to limit the open-circuit voltage of the welding transformer to about 100 volts r.m.s. There may then be a tendency for the arc to extinguish on voltage reversal across the arc gap at current zero, unless special means are adopted for its re-ignition. This tendency is more apparent for the half-cycles in which the work piece is about to become the cathode, and can result in half-cycle rectification. The investigations here deal with arc maintenance on the basis that welding is most satisfactory in the absence of rectification (or partial rectification—see Section 5.1).

The mechanism of rectification and its elimination for the tungsten rod-aluminium plate arc, in an atmosphere of argon, is of fundamental interest, as well as having considerable practical significance. The fundamentals of the problem involve the complex phenomena of arc re-ignition processes, so that the effects on arc re-ignition of various electrical parameters under typical welding conditions have here been studied.

An obvious parameter for examination is the open-circuit voltage of the welding transformer. Within the limits given below, the effects of this voltage on re-ignition have been investigated to determine the minimum voltage to avoid half-cycle rectification, both with and without auxiliary equipment for half-cycle re-ignition. An auxiliary device in common use injects a series of high-voltage high-frequency oscillatory sparks across the arc gap, which break down the gap that might otherwise have become non-conducting. The authors have previously examined typical characteristics of a spark injector unit.[2]

Figures are quoted in literature for the open-circuit voltage below which, in the absence of arc restriking devices such as h.f. spark injection, half-cycle rectification is encountered. These various values are, however, not necessarily comparable amongst themselves because of the differing characteristics of the several welding circuits, e.g., types of welding transformer, reactors, test materials, welding set-up, etc.

Some years ago Wassell[3] stated that " in the argonarc, rectification was complete if the open-circuit voltage was below a critical value which lay somewhere between 140 and 180 volts. The exact location of the critical open-circuit voltage seemed to be dependent on circuit constants, gas flow and arc length, but usually lay between these two values. Above a voltage of 180 volts for argon, little or no rectification of the current occurred." Later, Gibson and Rothschild[4] concluded that two standard 75 volt welding transformers " connected in series to give an effective 150 a.c. voltage, will give a uniform current wave and a stable arc."

Welch[5] says that " the usual a.c. arc welding transformer will not successfully operate an inert arc, as the open-circuit or restriking voltage required to start current flow for the half-cycles when the work is negative is far above that of the transformer. Arc welders generally have open-circuit voltages of the order of 75 volts r.m.s., but approximately 200 volts are required for consistent stability of an arc in argon"

High-frequency spark injection permits the use of lower

open-circuit voltages. It may be noted that Gibson and Rothschild[4] state that " the use of a standard 75-volt welding transformer with an oscillator was not satisfactory because the positive half wave of the current cycle varies because of the erratic nature of spark gap oscillators." A previous paper by the present authors has shown how to use such oscillators satisfactorily[2], and the work is here extended to cover a range of open-circuit voltages.

Further it is claimed[4] that eliminating the d.c. component encountered in the argonarc improves welding performance. Welch[5] states that its suppression, by the insertion of a low-voltage series capacitor in the welding circuit, greatly increases arc stability and that " by a moderate increase in secondary voltage—75 increased to 100 volts—it is possible to eliminate the high-frequency pilot." Data on the effects of a large series capacitor on arc re-ignition are given in this present report.

Sillifant and Woollcott[6], referring to a circuit without h.f. spark injection or series capacitor, state that " current rectification can be eliminated by employing transformers with high open-circuit voltages in the region of 240 volts and upwards, but considerations of safety, high cost and low power factor preclude their use."

Clearly the relation of open-circuit voltage to the welding circuit and its characteristics, etc., requires further examination and this report deals with an oscillographic analysis of the effects of open-circuit voltage on re-ignition of the argonarc, using recording equipment with time resolutions extending from hundredths of seconds down to microseconds.

2. SCOPE OF INVESTIGATIONS

This report is illustrative and is not so much concerned with establishing open-circuit voltages for the avoidance of rectification for this process, as with demonstrating broadly the factors which determine such voltages.

Comprehensive lists of open-circuit voltages would entail work over ranges of voltage at given currents, for circuits with given electrical characteristics. Various materials would have to be studied, including aluminium alloys and pure aluminium, with various surface preparations prior to test, whilst the effects of gap length, rate of argon flow, traverse rate, etc., would need consideration.

The investigations refer to tests on two work plate materials over a range of open-circuit voltage, at approximately constant current, both with and without high-frequency spark injection, on a circuit deriving power from a leaky-reactance type welding transformer, both with and without a large series capacitor in the welding circuit.

For these particular tests the investigations do establish the open-circuit voltages for the avoidance of rectification. These are sufficiently diverse to show the danger of generalizing statements on open-circuit voltages for this process. The results explain the wide discrepancies apparent in the figures quoted in previous literature. Also considered here, however, is the broader and more fundamental question of the nature of the arc re-ignition. The data throughout apply to the arc after it has been running for some time, and not to the initial stages of starting from cold, i.e., the rod and work plate are hot and have substantially reached equilibrium.

3. TEST TECHNIQUE

3.1. Welding Equipment

The test equipment was as described in an earlier publication[2] with the addition of an auto-transformer and a second welding transformer, similar to the first, to extend the range of open-circuit voltages available (see Fig. 1).

By suitable combinations of the auto-transformer and the primary and secondary tappings of the 10 kVA leakage-reactance type welding transformer, the following open-circuit voltages could be selected, viz. : 45, 60, 85, 95, 105, 115, 125 volts r.m.s. Addition of the second welding transformer (primary in parallel and secondary in series with the first) gave 140, 150, 160, 175 volts r.m.s.

The series capacitance inserted for some tests was 0·25 F. Without this capacitance the current asymmetry associated with the argonarc was of course present, together with the additional asymmetry introduced if appreciable current zero pause existed before the re-ignition of the reverse polarity half-cycle (see Section 5.4. in Ref. 2).

A commercial high-frequency spark oscillator was used for arc re-ignition when required, a phase-shifting transformer in its input enabling the group of sparks to be injected either around the current zero (" well phased " giving optimum chance of " early " re-ignition), or late in the half-cycle (" late phased ").

A water-cooled argonarc hand welding torch was fitted with a 3/32" diameter tungsten rod, and was clamped to an electrically driven traverse machine. The test work pieces were $12'' \times 4'' \times \frac{1}{4}''$ plates of an Al-5% Mg alloy, surface degreased or scratch-brushed, and similar plates, but $\frac{1}{8}''$ thick, of commercially pure aluminium (2L4), surface scratch-brushed. The alloy work plates were clamped to, but spaced from, a brass table top, but the thinner aluminium plates were clamped directly thereto. The earth return lead ran symmetrically from beneath the test plates.

3.2. Recording Equipment

As the recording equipment has been described elsewhere[7, 8] full details are not given here. The electromagnetic oscillograph unit recorded on a time scale of 10 millisec./cm., (a) supply mains voltage, (b) current in the main welding circuit, (c) voltage across the arc gap, (d) voltage across the spark gap of the h.f. injector, (e) voltage across the series capacitor.

The medium-speed cathode-ray oscillograph unit recorded, with good resolution, the voltage across the arc gap together with the superposed voltage from the h.f. injector, when in use, on a time scale of 3 millisec./cm. Using the timing drum control these two units were synchronized and recorded over a period of 1 second[7].

The arc gap voltage (and superposed h.f. injection) was also recorded at high speed, using a cathode-ray oscillograph with a recurrent electronic time sweep, in conjunction with a drum camera[8]. The time scale on the resultant saw-tooth record was about 100 microsec./cm. on the stroke, i.e., about thirty times faster than on the medium-speed c.r.o. unit, and 10 microsec./cm. on the fly-back. This unit recorded for a period of 0·04 sec. in the middle of the main recording period of 1 sec.

3.3. Test Procedure

Melt runs, 6 cm. long, were made without a filler rod, at a series of open-circuit voltages from 45 to 175 volts r.m.s., at an approximately constant current of 80 amp. r.m.s. When two welding transformers were used in series (for voltages above 125) each was adjusted separately to give the same short-circuit current, so that together their operation was suitably balanced. The usual arc gap was $\frac{1}{4}''$, traverse rate 1 mm./sec., and argon gas flow (purity 99·8%) adjusted to read 4 litres/min. on an oxygen type flow meter.

With the power circuit energized, the arc was initially ignited by the h.f. spark injector unit, and the traverse started. The h.f. injection was required throughout the run at the lower voltages, but could be switched off at the higher. The oscillographic units were operated 45 sec. after arc initiation, by which time the system was assumed to have reached a state of quasi-equilibrium, so that the recording could be taken as typical of the run.

In addition to controlling the recording equipment, the timing drum unit could switch the h.f. spark injector in or

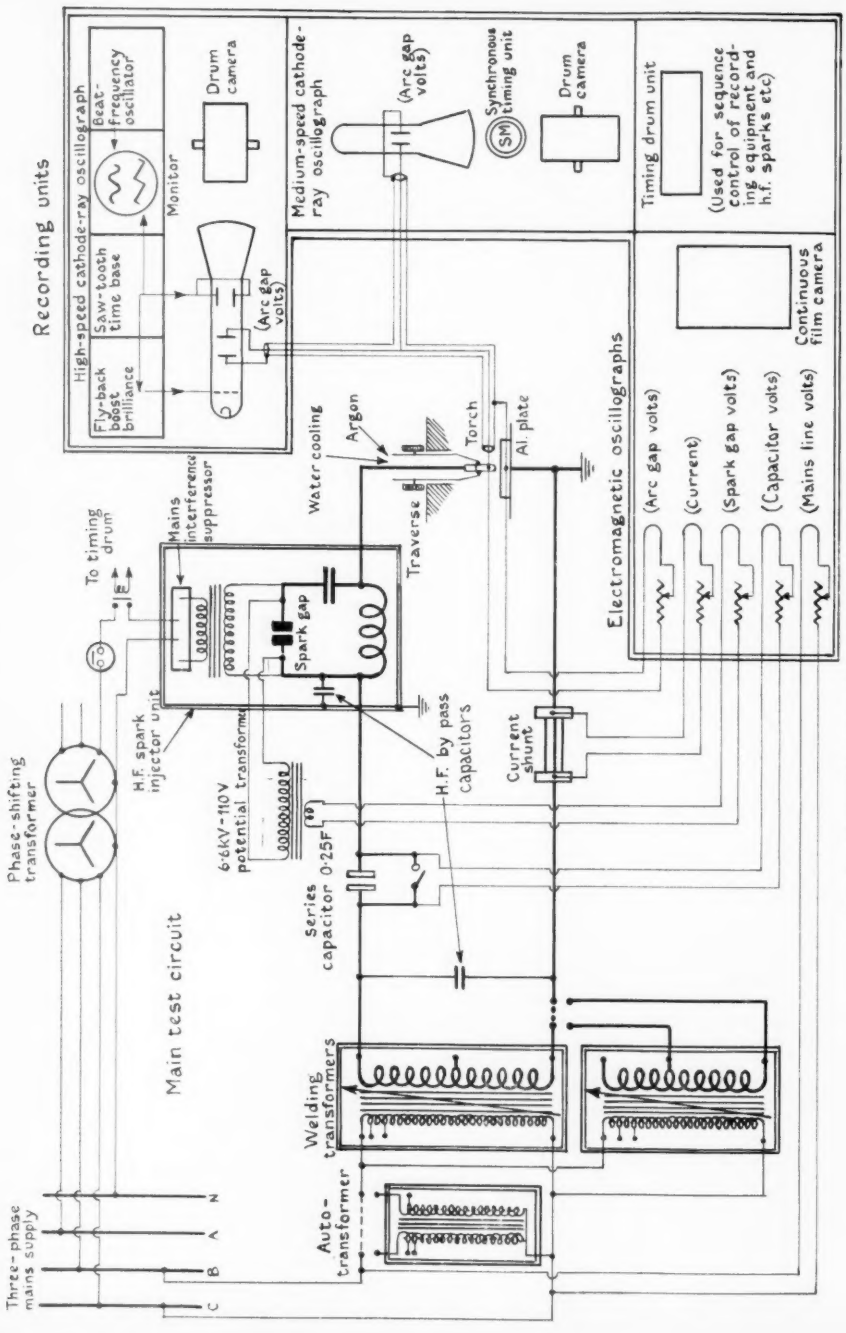


Fig. 1.—Schematic diagram of test and recording equipment.

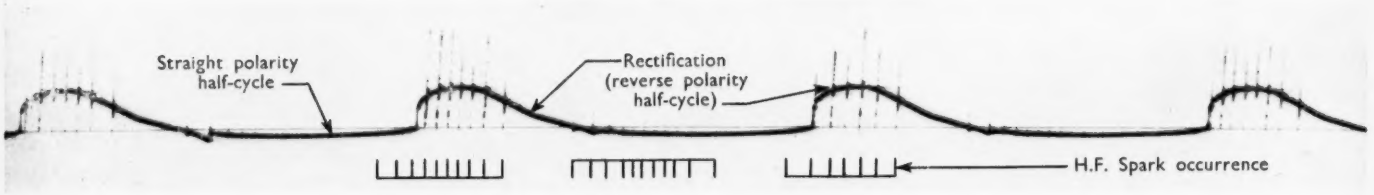


Fig. 2(a).—Type (A) Rectification in spite of h.f. spark injection.

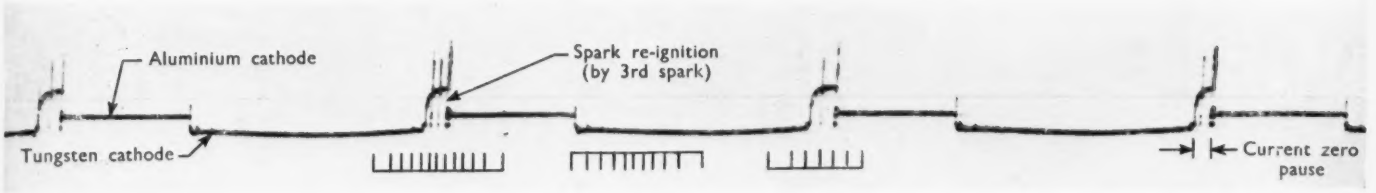


Fig. 2(b).—Type (B) Spark re-ignition—more than one spark required.

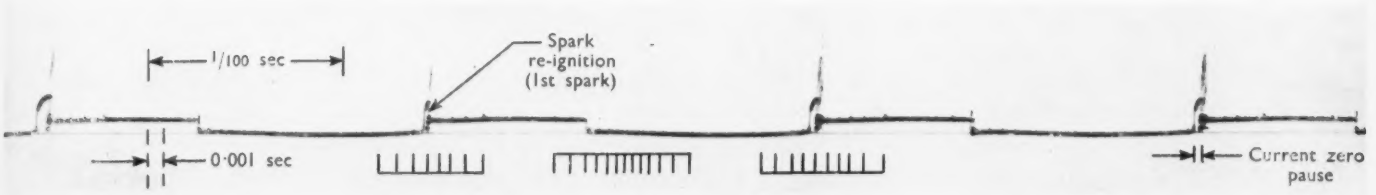


Fig. 2(c).—Type (C) Spark re-ignition—first spark.

Fig. 2.—Oscillograms of re-ignition types A, B and C, using h.f. spark injection. *(See Section* 4.1.)

Calibration. Time— ⬌ 3 millisec./cm. Volts $\frac{+ve}{-ve}$ 85 volts/cm.

Note : *In the reproduction of* 2, 5 *&* 11, *the time of occurrence of the injected h.f. sparks has been indicated for certain half-cycles by a "tooth comb" drawn beneath the oscillogram.*

out within the oscillographic recording period. The series capacitor could be inserted into the welding circuit, at any time during the test run or recording period, by a heavy-duty snap-action knife switch.

4. EXPERIMENTAL DATA

4.1. General

As already stated the present investigations deal with arc maintenance on the basis that the absence of half-cycle rectification (or of late breakdown—see Section 5 in Ref. 2) results in the most satisfactory welding conditions. The appearance of the melt run on the work plate was very sensitive to changes in overall arc behaviour and, quite apart from the oscillographic data, provided an indication of the adequacy of the test conditions for welding.

In this work five distinct stages of arc re-ignition have been recognized as the open-circuit voltage was raised from lower than was satisfactory even with well-phased h.f. injection, to higher than was necessary for a self-maintaining arc in the absence of spark injection. The first three stages apply to conditions using h.f. injection, and the last two to self re-igniting arcs, viz. :—

Type (*A*)—Complete rectification in spite of h.f. injection, as shown in Fig. 2 (a). The sparks are well phased, and yet fail to establish the reverse polarity arc. The welding of aluminium cannot be accomplished under these conditions.

Type (*B*)—More than one spark required before the reverse polarity half-cycle re-ignites (see Fig. 2 (b)). Again, the sparks are well phased, but the failure of the first few sparks to cause re-ignition results in a long current zero pause in the half-cycle, and consequently in a small reverse polarity current loop.

Type (*C*)—First available spark re-ignites the arc regularly, Fig. 2 (c). With the h.f. sparks well phased the mean current zero pause is small, giving a large current loop and small d.c. component. This is the optimum that a commercial high-frequency spark injector unit can achieve, and results in good clean melt runs.

Type (*D*)—Self re-ignition of the arc after a short interval at the start of the reverse polarity half-cycle (Figs. 3 (a) and (b)). During this interval the voltage is high, but significantly less than the open-circuit voltage of a rectifying half-cycle. This condition is here termed a "soft gap." The resultant current loops are much as for (*C*) above.

Type (*E*)—Self re-ignition of the arc immediately following the straight polarity arc (Fig. 4). This gives the maximum conduction and the minimum d.c. component.

The inherent mean d.c. components above can of course be eliminated by inserting a large series capacitor in the welding circuit, but this does not in itself alter the mean current zero pause, which depends on the phasing of the h.f. sparks and/or the type of arc re-ignition. The longer the zero pause the less the current delivered by the welding transformer under given conditions.

The high-speed oscillograms reveal the details of these several re-ignition stages which are described fully in Section 6. For the straight polarity half-cycles (i.e., in which the tungsten electrode becomes the cathode), in all cases in which the preceding reverse polarity arc had been ignited, the arc re-struck, without requiring auxiliary means such as spark injection, down to the lowest value of open-circuit voltage used, viz. : 45 volts r.m.s. Following a rectified half-cycle however, the tungsten arc did not re-strike without h.f. spark injection unless the gap was much less than $\frac{1}{8}''$, because the self re-ignition voltage for the straight polarity half-cycle increases very rapidly as the gap is lengthened, and about $3/32''$ was the maximum that could be held. (See Figs. 13 (a) and (b), and Section 5.2.).

4.2. "Critical" and "Minimum Satisfactory" Open-Circuit Voltage

With increase in open-circuit voltage the arcing changed from the reverse polarity half-cycles rectifying in spite of h.f. injection, to their being struck by the sparks, and finally to their becoming self re-igniting, the argonarc then being completely self-running.

Tables 1 and 2 give the minimum satisfactory transformer voltages for welding determined for the various test arrangements, together with, as a lower limit, the critical or borderline voltages. The critical voltage given in Column 1 of the tables is, in the case of h.f. spark injection, the lowest that avoided rectification, but often more than one spark was needed to ignite the reverse polarity half-cycles. Thus, using well-phased h.f. injection, arcing was a mixture of re-ignition types (*B*) and (*C*) without type (*A*).

The minimum satisfactory voltage with spark injection, Column 2, is that for which the first spark re-ignited the arc in some 90 per cent. of the half-cycles concerned, i.e., re-ignition mainly type (*C*). The remaining 10 per cent. required, in general, two sparks because the first occurred during the rapid voltage rise following the end of the straight polarity half-cycle, and before adequate open-circuit voltage was available. This is due to the random timing of individual sparks within a spark group.

The critical voltage for self re-ignition was less easy to determine, since h.f. injection had to be used to re-strike the arc in case it ever failed to re-ignite from the higher open-circuit voltage alone. In some tests to determine this critical voltage, therefore, the h.f. sparks were so phased that there was no injection over the period immediately following the straight polarity arc, when self-breakdown could occur from the high open-circuit voltage. If the arc failed to self re-ignite, then the spark served to re-strike it later in the half-cycle, as shown for instance in Fig. 5 (a). In other tests with well-phased h.f. injection, analysis of the oscillograms showed that the arc was actually self re-igniting (type (*E*)), and not directly dependent on the sparks (see Fig. 5 (b)). This record is seen to be very similar to Fig. 4, in which there was no spark injection. The zero pause in Fig. 5 (b) is negligible compared with that resultant on the optimum use of the h.f. sparks, Fig. 2 (c), and in many half-cycles a spark clearly occurred both before and after, but from their spacing, not during the actual re-ignition stage. Again, in certain cases, the arc was self re-igniting with h.f. present and apparently not directly required, but the arc extinguished on switching off the sparks. This appears to be a slight stablizing effect of the sparks under these critical conditions apart from their primary use in breaking down the gap which would otherwise have become non-conducting. From these tests in which the arc self re-ignited for some 90 per cent. of the cycles recorded (either types *D* or *E*) without directly using the h.f., the open-circuit voltage was classed as critical (Column 3 in the tables).

The minimum satisfactory voltage for self re-ignition (Column 4) is that for which the h.f. injection could be removed after first starting the run, and at the end of the run the gap could be increased to $\frac{1}{4}''$ or greater.

4.3. Open-Circuit Voltage and Arc Behaviour

The number of the cycles of each re-ignition type was determined by analysis of the oscillograms at the various open-circuit voltages, for each combination of plate material, h.f. injection, and series capacitor. This information, which forms the basis of Tables 1 and 2, can be represented graphically. In Fig. 6 the ordinates represent the relative percentage occurrence of the re-ignition types against open-circuit voltage for the aluminium alloy, both degreased and scratch-brushed, and similarly in Fig. 7 for scratch-brushed commercially pure aluminium.

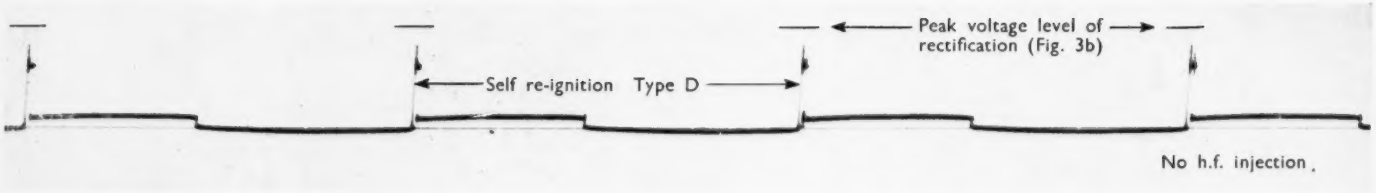


Fig. 3(a).

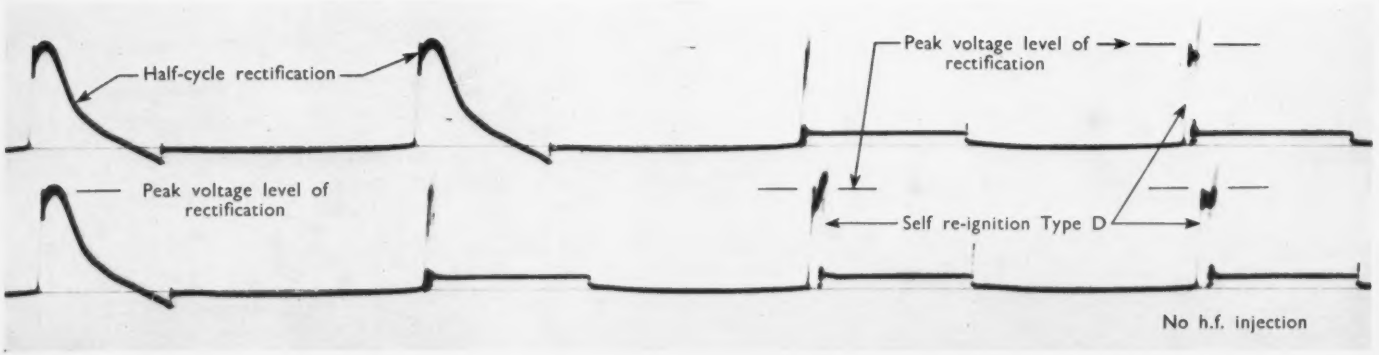


Fig. 3(b).

Fig. 3. Oscillograms showing delayed self re-ignition type D (soft gap). (*See Section* 4.1.)
Calibration. Time ⟶ 3 millisec. cm. Volts ↑ +ve 85 volts/cm.

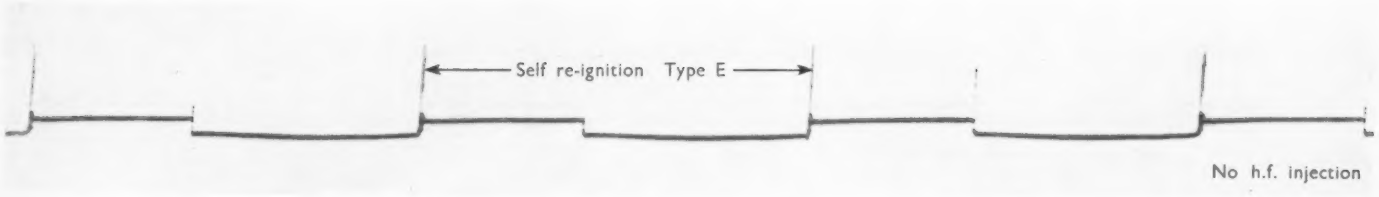


Fig. 4.—Oscillogram of self re-ignition type E.
(*See Section* 4.1.)

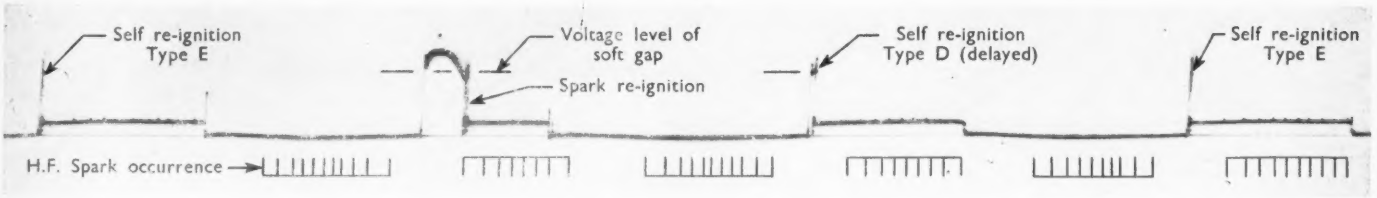


Fig. 5(a).—H.F. sparks phased late in half-cycle.

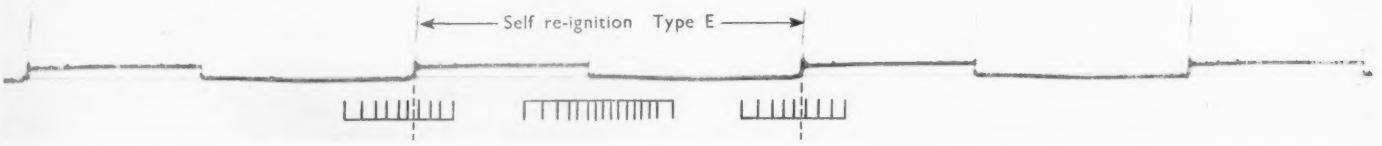


Fig. 5(b).—H.F. sparks well phased but breakdown not directly dependent on spark.
Fig. 5.—Oscillograms at the critical voltage for self re-ignition. (*See Section* 4.2.)
Calibration. Time → 3 millisec./cm. Volts $\frac{\uparrow}{-}$ + ve 85 volts/cm.

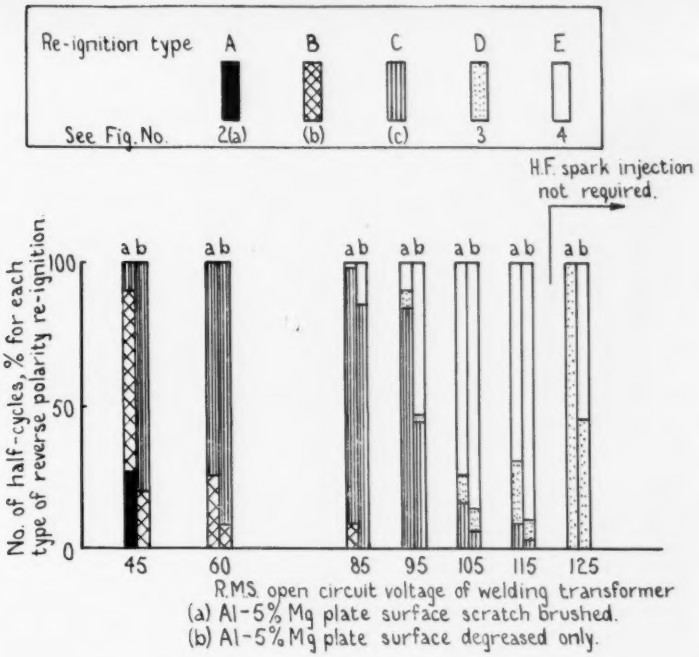


Fig. 6.—Effect of open-circuit voltage on arc re-ignition for Al-5% Mg.

Although there is no sharp demarcation, and at any given voltage there is in general more than one type of re-ignition, these figures show clearly the transition in the re-ignition stages with increasing open-circuit voltage, from being dependent on, to independent of, h.f. injection. Further, Fig. 6 shows that throughout, the degreased Al-5% Mg is easier to re-ignite than the same material scratch-brushed; and that when the h.f. sparks are not directly used, the scratch-brushed alloy has a greater tendency to the delayed self re-ignition, type (*D*) (soft gap). Similarly, comparing Fig. 7 with Fig. 6 shows that arc re-ignition with commercially pure aluminium is more difficult than with the alloy, under the same test conditions.

The oscillographic examination of the arc is more sensitive than, say, the appearance of the resultant melt run, although this is a helpful criterion to assess welding performance in practice. For instance, the occasional loss of a part or all of a half-cycle would not seriously affect a melt run in appearance, but the loss would be revealed on the oscillographic record of the arc gap voltage. However, if the arc re-ignition is consistently late in the half-cycle, or if marked rectification occurs, then the greatly reduced reverse polarity current and heavy d.c. component would impair the melt run. For example see Figs. 8 (a) to (f) which are photographs of melt runs on scratch-brushed aluminium for open-circuit voltages of 45, 60, 85, 105, 125 and 160 volts r.m.s., and the corresponding re-ignition types for these voltages as shown in Fig. 7. The re-ignition types and resultant melt runs change with voltage, but above 105 volts r.m.s. the runs are substantially the same, although the oscillograms show an increasing degree of self re-ignition until, at 160 volts r.m.s., the spark injection can be removed. This implies that from the welding aspect so long as the arc conducts for most of each reverse polarity half-cycle, the type of arc re-ignition is relatively unimportant except insofar as it determines whether the arc re-ignites at all for a given circuit.

The general arc behaviour noted at the various open-circuit voltages was as follows :—

45 volts r.m.s. :

In spite of well-phased h.f. injection, rectification occurred in 80 per cent. of the reverse polarity half-cycles (and the remainder were not full current loops). This resulted in a rough pitted and blackened (or dark grey) melt run with some bright patches corresponding to the brief periods of late re-ignition (Fig. 8(a)). The current, as indicated on a meter, was much lower than expected, with brief surges to higher values and similarly the hum from the transformer was erratic or " bumpy." The arc spluttered and progressed in short jumps forming a series of small discontinuous melt pools.

60 volts r.m.s. :

Although rectification occurred as frequently as did conduction for part of the half-cycle (mostly late re-ignition), the melt run was much improved on the above, showing flat bright or white molten pools interrupted by rough black pitting (Fig. 8 (b)). Again the arc spluttered with erratic sound and varying current from the transformer, but it repeatedly formed a molten pool and then appeared to move erratically about until it settled and formed a fresh pool.

85 volts r.m.s. :

Well-phased h.f. injection entirely eliminated rectifica-

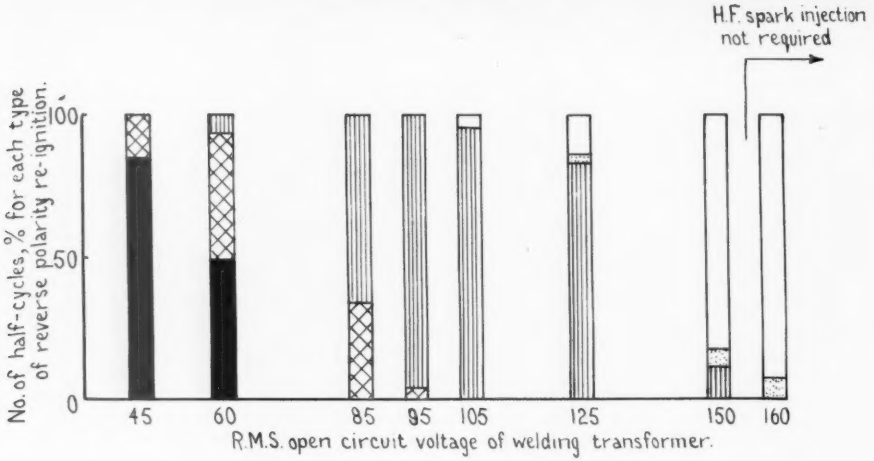


Fig. 7.—Effect of open-circuit voltage on arc re-ignition for commercially pure aluminium (scratched brushed).

tion and the melt run was again improved, having a continuous matt white and flat central track with a bright crater (Fig. 8 (c)). The arc and pool progressed steadily, but as one third of the reverse polarity half-cycles had small current loops (where more than one spark was required to re-ignite the arc) the current reading was lower than expected, the molten pool was small and not well formed, and the final crater uneven. (The cracks in the run are due to insufficient penetration of the test piece with the consequent constraint.)

150 volts r.m.s. :

This melt run, Fig. 8 (d), was slightly improved on that at the critical voltage for spark maintenance, Fig. 8 (c), since reduced current loops were eliminated. The arc was steady with a smoothly moving, continuous melt pool with steady current and sound from the transformer, giving a flat matt white run and a bright flat crater (the final melt pool).

125 volts r.m.s. :

The melt run, Fig. 8 (e), was substantially the same as Fig. 8 (d) since, with well-phased h.f. injection, the first spark in the reverse polarity half-cycle successfully re-ignited the arc and almost as satisfactory current loops resulted at the lower open-circuit voltages as did from self re-ignition at the higher.

160 volts r.m.s. :

The melt run, Fig. 8 (f), was again substantially the same as Fig. 8 (d), although self re-ignition was 100 per cent. and h.f. sparks were not required. This requires about double the open-circuit voltage for critical spark re-ignition.

For both work plate materials there is a large voltage difference between the state of rectification, in spite of well phased h.f. injection and that where the arc is self-running. As shown above, within this voltage range the increase of self re-ignition with increasing voltage is not particularly advantageous in practice until it becomes 100 per cent. If, however, the h.f. is badly phased, giving late breakdowns or even rectification, then raising the open-circuit voltage increases the occurrence of self re-ignition and consequently the number of full current loops, and so results in a marked improvement in the melt run. To a limited extent, this effect can be demonstrated by inserting a large series capacitor in the welding circuit during a run, this in general being equivalent to raising the open-circuit voltage by about 15 volts r.m.s. (see Section 7 and Tables 1 and 2). Figs. 9 (a) and 9 (b), referring to the alloy and to aluminium respectively, show on the left-hand section of each photograph the appearance of the run without a series capacitor, and on the right-hand section the run after its insertion.

It is interesting to note that with a leaky-reactance type transformer, satisfactory melt runs and arc re-ignition characteristics were obtained on degreased Al-5% Mg alloy, using well-phased h.f. spark injection and a series capacitor at an open-circuit voltage as low as 45 volts r.m.s. (see Fig. 10).

5. RE-IGNITION OF THE A.C. ARGONARC

5.1. Definitions

To facilitate the discussion in the subsequent sections, the following definitions, terms and symbols will be used as given below and shown in Fig. 11 :—

W-arc : An arc, burning between the tungsten rod and the work plate, with its cathode on the tungsten. (Similarly W-h.c. is the straight polarity half-cycle, i.e., rod negative with respect to the plate whether an arc is present or not).

Al-arc : An arc with its cathode on the work piece, either aluminium or aluminium alloy. (Similarly Al-h.c. is the reverse polarity half-cycle with the tungsten rod positive to the work plate.)

Gap voltage : The voltage between the rod and plate. When a power arc is established the gap voltage is the arcing voltage.

Restriking voltage (R.V.) : The voltage which appears across the gap immediately after arc extinction. This voltage may be considered as composed of two components, one of mains frequency and a transient component (which may be oscillatory), referred to as the transient R.V.

Inherent restriking voltage : The restriking voltage associated with a particular circuit and determined by the circuit parameters alone, its form being unmodified by the conditions in the gap.

Time →

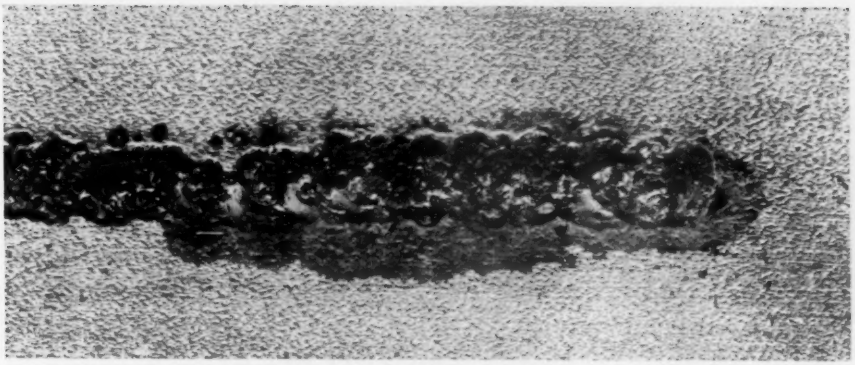


Fig. 8(a).—Open circuit volts 45 r.m.s.

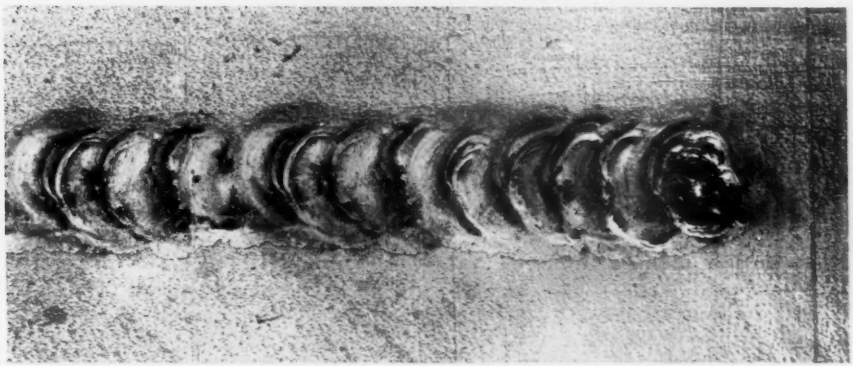


Fig. 8(b).—Open circuit volts 60 r.m.s.

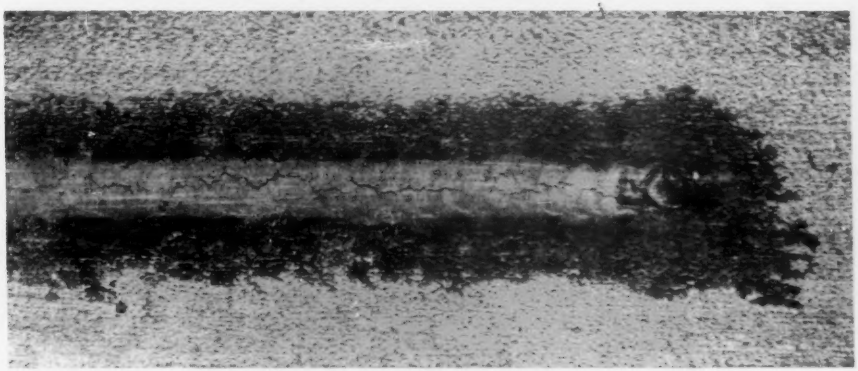


Fig. 8(c).—Open circuit volts 85 r.m.s.—critical voltage for re-ignition of arc by h.f. sparks.

Fig. 8.—Melt runs on aluminium (2L4, surface scratch brushed) against open circuit voltage.
(*See Section* 4.3 *and Fig.* 7.)

Note: ***Well phased h.f. injection for 'a' to 'c.' Photographs enlarged*** ×4.

Time →

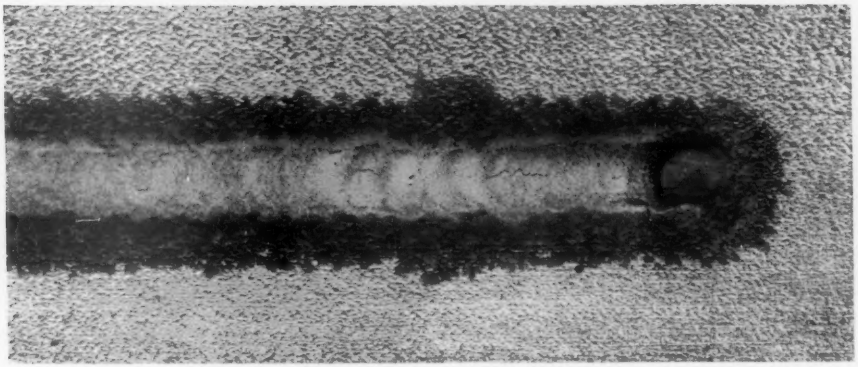


Fig. 8(d).—Open circuit volts 105 r.m.s.

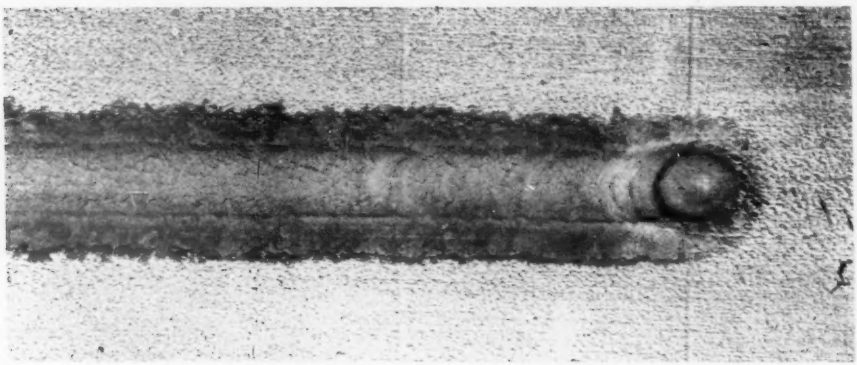


Fig. 8(e).—Open circuit volts 125 r.m.s.

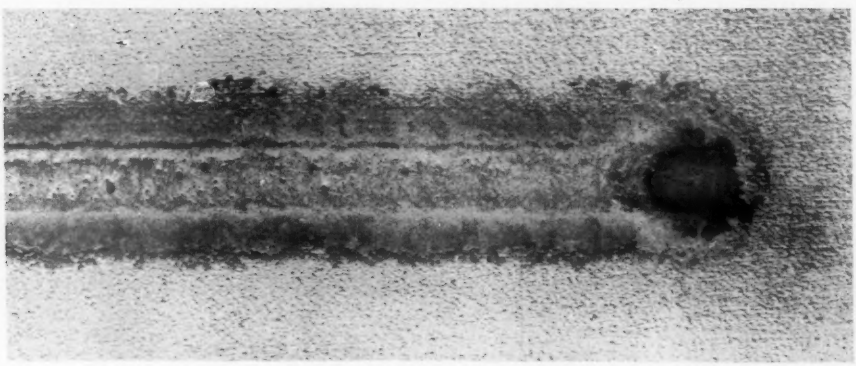


Fig. 8(f).—Open circuit volts 160 r.m.s.—minimum satisfactory voltage for self re-ignition of arc.

Fig. 8.—Melt runs on aluminium (2L4, surface scratch brushed) against open circuit voltage.
(See Section 4.3 and Fig. 7.)
Note: *Well phased h.f. injection for 'd' and 'e' but no h.f. injection for 'f.' Photographs enlarged* ×4.

Time →

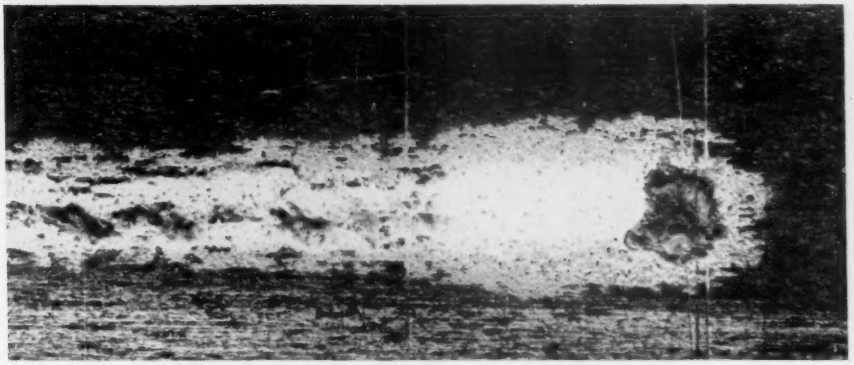


Fig. 9(a).—Al-5% Mg, surface degreased, open circuit volts 95 r.m.s.

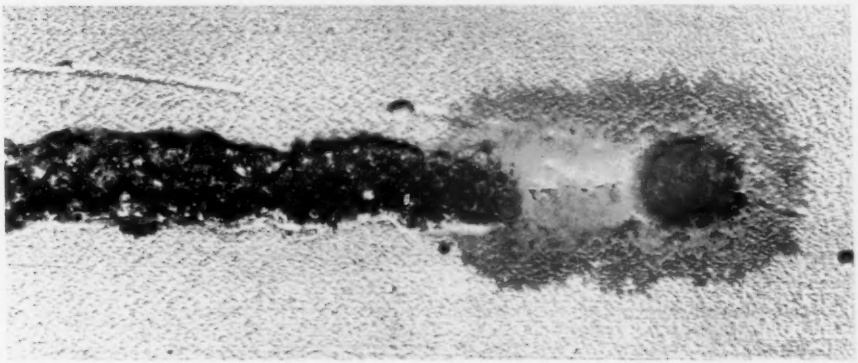


Fig. 9(b).—Al 2L4, surface scratch brushed, open circuit volts 105 r.m.s.

Fig. 9.—Melt runs near critical open circuit voltage for self re-ignition showing improvement due to inserting a large series capacitor. (*See Sections* 4.3 *and* 7.1.)

Note: *Left hand part of run before, and right hand part after capacitor inserted with h.f. injection late phased throughout. Photographs enlarged* ×4.

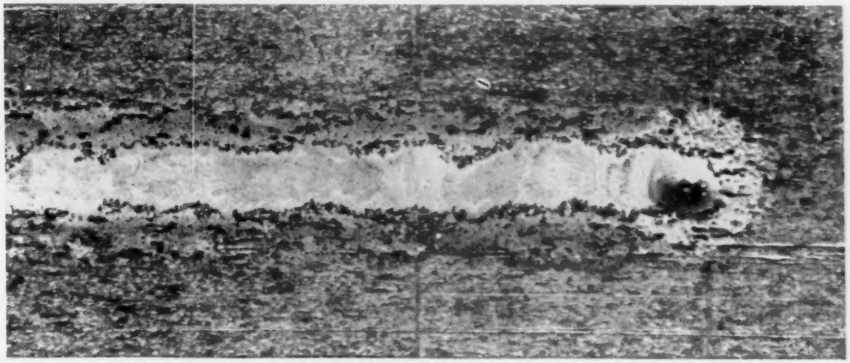


Fig. 10.—Melt run on Al-5% Mg (surface degreased) at 45 volts r.m.s. open circuit. (*See Section* 4.3.)

Note: *Well phased h.f. injection and large series Capacitor. Photograph enlarged* ×4.

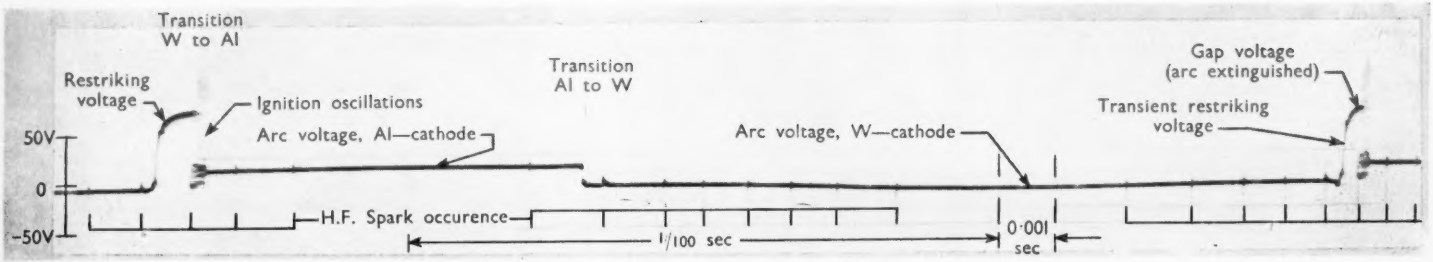


Fig. 11.—Typical gap voltage oscillogram of the argon arc with h.f. spark injection.
(See Section 5.1.)

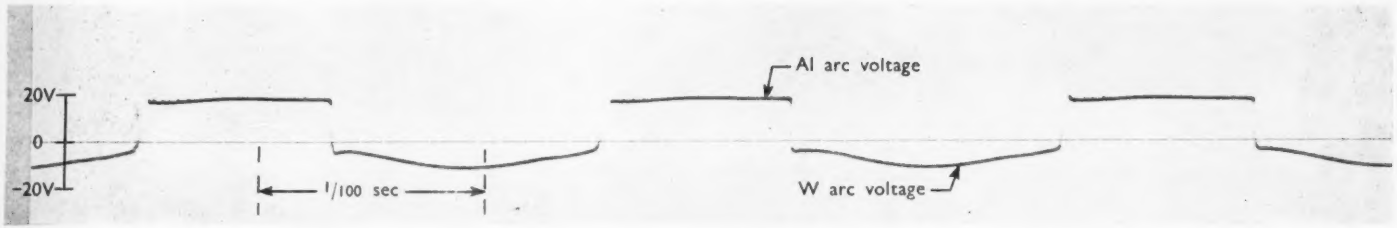
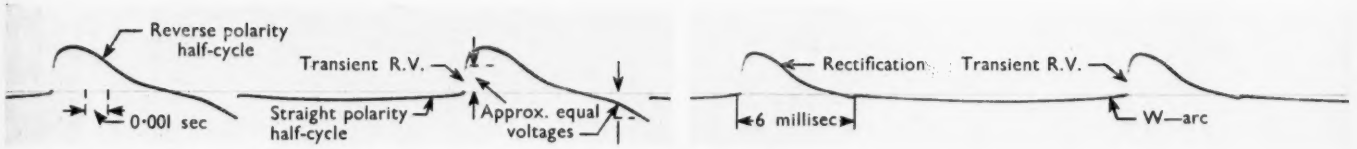


Fig. 12.—Detail of the arc voltage of the argon arc.
(See Section 5.2.)

Notes: (1) *The h.f. sparks disturb the arc to some extent and the effect appears as a small pip in the arc voltage record.*
(2) *The fast voltage-changes, viz., transient restriking voltage, ignition oscillation and the transition from Al-arc to the W-arc. Fig. 11, are not recordable at this sensitivity and beam intensity.*
(3) *The h.f. injection is well phased, starting the Al-arc early in the reverse polarity half-cycle.*



(*a*) Gap $\frac{1}{16}$ in.

(*b*) Gap $\frac{1}{32}$ in.

Fig. 13.—Oscillogram of a rectifying arc.
(*See Section* 5.2.)
Time → 3 millisec./cm. Volts ↑ +ve 85 volts/cm.

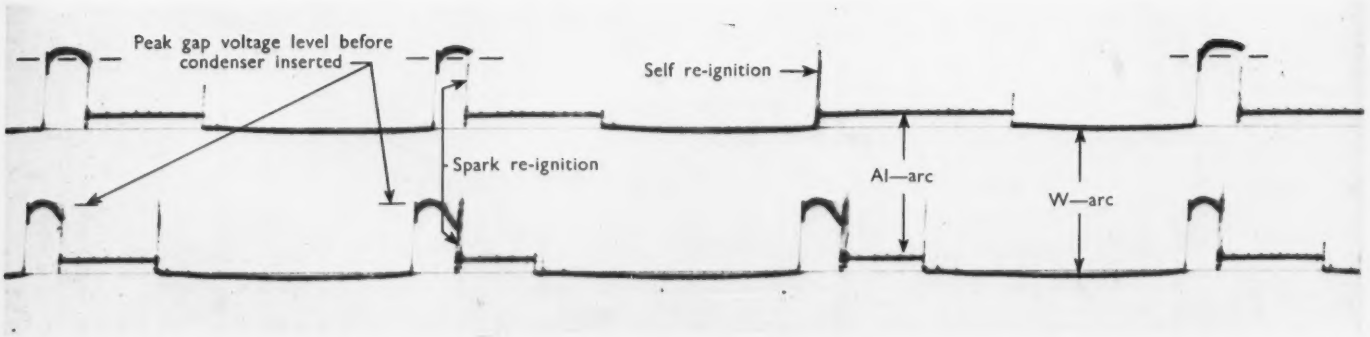


Fig. 14.—Oscillogram showing increase of restriking voltage due to series capacitor. (*See Section* 7.2.)
Time → 3 millisec./cm. Volts ↑ +ve 85 volts/cm.
Note: *Capacitor inserted* 7 *cycles after end of lower strip and* 4 *cycles before beginning of upper strip.*

Rectification : Here the term rectification means the complete loss of a reverse polarity current loop, i.e., the argonarc acts as a half-wave rectifier.

Partial rectification : The arc extinguishes at the end of the W-h.c. as in rectification, but is re-ignited by, say, spark injection during the Al-h.c. (The greater the time delay from W-arc extinction to Al-arc re-ignition, i.e., current zero pause, the smaller the subsequent current loop in amplitude and duration.)

Inherent rectification : The unbalance of current loops (or half-cycles), even with immediate re-ignition of the Al-arc following the W-arc, and vice versa. This is due to the higher impedance of the arc with its cathode on the work piece than on the tungsten electrode, resulting in a d.c. component unless preventive measures are taken.

Self re-ignition : The sudden breakdown of the gap from the restriking voltage to an arcing condition, without auxiliary means for initiating the breakdown. (At a sufficiently high open-circuit voltage self-breakdown occurs regularly and the arc becomes self-running.)

Spark re-ignition : The breakdown of the gap to arcing conditions as above, but initiated by the high voltage injected by a h.f. spark oscillator. (This implies a lower open-circuit voltage than for self-breakdown, the spark re-igniting the arc as in partial rectification.)

Soft gap : A condition of the gap after arc extinction in which there appears to be appreciable remanent conduction, thereby modifying the restriking voltage and possibly the arc re-ignition process.

Ignition oscillations ; The complex voltage oscillations and transients which generally accompanied the formation of the Al-arc proper, following spark or self-breakdown of the gap.

5.2. General

With a geometrically unsymmetrical electrode system of different materials as in the a.c. argonarc process, the arc has differing characteristics for the two polarities. In particular cases these differences can result in conduction for one half-cycle and total rectification for the other.

The arc is more stable with the tungsten rod, than with the work plate, as cathode. The oscillogram in Fig. 12, shows that for the W-arc the arc voltage is lower than for the Al-arc and has a slight positive characteristic (i.e., it rises with increasing current in the half-cycle), and near the end of the half-cycle the voltage falls steadily though rapidly towards zero. The Al-arc voltage is substantially constant throughout the reverse polarity current loop, implying that the Al-arc resistance is high at low currents.

Further, at the end of the half-cycle the Al-arc voltage does not fall smoothly to zero but abruptly leads to the W-arc. In many cases there is a short-duration positive voltage rise before the transition, as shown for instance in Fig. 11, indicating that the arc extinguishes (or greatly increases in resistance) just prior to the end of the half-cycle.

Starting from cold, high voltages are required to break down the gap and initiate an arc—cf. the voltage applied by the high-voltage high-frequency spark oscillator. When, however, the electrodes and the gases in the gap are hot, low voltages will cause breakdown. Thus, in general, immediately following arc extinction, re-ignition is effected by lower voltages the sooner they are applied.

The re-ignition characteristics of the Al- and W-arcs are even more dissimilar than their arc voltage characteristics. For instance, Fig. 13 (a) shows a steadily rectifying argon arc h.f. injection not being used, and the open-circuit voltage being insufficient to cause self-breakdown of the Al-arc. Here, in the W half-cycle the gap broke down at approximately 50 volts and formed an arc some 9 millisec. after the preceding W-arc, whereas in the Al half-cycle a similar voltage (the transient R.V.) applied within 20 micro sec. of W-arc extinction did not break down the gap and rectification occurred. For a still shorter gap setting, the W-arc re-ignited at an even lower voltage and with a smoother voltage characteristic 6 millisec. after the previous arc (see Fig. 13 (b)). It follows that, in the absence of arc restriking devices (e.g., h.f. spark injection), if the arc once fails to re-ignite on the W half-cycle, then total arc outage will result.

The re-ignition of the W-arc, immediately following an Al-arc, occurs at a very low voltage (see Fig. 12), and it appears that the straight polarity arc is formed (i.e., an arc voltage is established) almost immediately the voltage across the gap reverses. The Al-arc re-ignition, however, requires voltages of the order of 100 volts and upwards applied soon after the W-arc extinguishes, and the re-ignition process itself is much more complex, with, in general, a series of ignition oscillations before the Al-arc is finally established at an arc voltage of about 20 volts (e.g., see Fig. 11). These ignition oscillations of the Al-h.c. are considered in greater detail below.

6. RE-IGNITION OF THE ARC WITH ALUMINIUM AS CATHODE

6.1. Self Re-Ignition (from Transient Restriking Voltage)

With a sufficiently high open-circuit voltage on the welding transformer, the h.f. injection can be removed and the argonarc is self-running. At the beginning of each Al half-cycle the transient R.V. was immediately followed by the ignition oscillations, which appear as a characteristic blur on the medium-speed oscillograms such as Fig. 4. (These ignition oscillations are shown more clearly in Fig. 11, but separate from the transient R.V. because the Al-arc was spark re-ignited.) The band of oscillations has three main levels, the top one of the order of the R.V., and the lower two similar to the Al- and W-arc voltages, with apparently rapid transitions between these regions. The oscillatory re-ignition process is resolved on the stroke of the electronic saw-tooth time base of the high-speed cathode-ray unit (see Fig. 15 (a)) whilst still further detail is shown on the fly-back (see Figs. 15 (b), (c), (d)). For clarity, Figs. 15 (a) and (b) have been drawn out with time running continuously from left to right as shown in sketches 16 (a) and (b) respectively.

From a study of many such high-speed oscillograms the characteristics of these Al-arc re-ignitions appear to be:—

(i) Following the breakdown of the gap at a high positive open-circuit voltage on the transient R.V. an arc-voltage level of the same order and polarity as the Al-arc voltage is formed.

(ii) The first arc-voltage level above rapidly reverses to a low potential of similar characteristics to the W-arc.

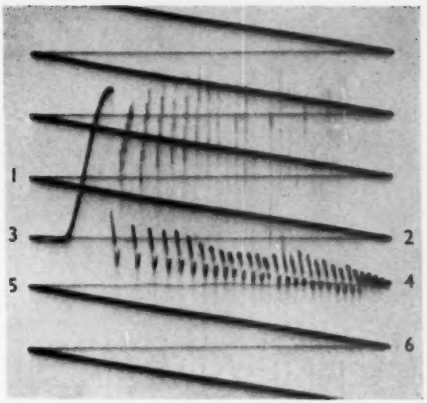
(iii) Following this second arc-voltage level the gap voltage again rapidly rises in the positive direction to the next breakdown.

(iv) The subsequent transient voltage-rises are all faster than the initial transient R.V. and also become more rapid throughout the series of ignition cycles. Each rise consists of two parts, the first very rapid which generally excites oscillations on the following slower rise.

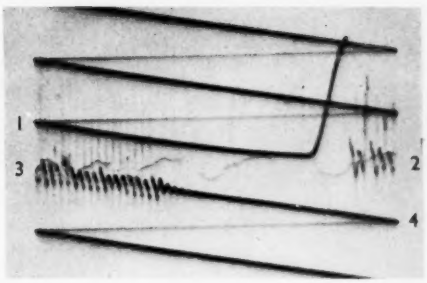
(v) The amplitude and duration of the loops corresponding to the second arc-voltage level decrease throughout the re-ignition period, until the last breakdown leads to the final Al-arc voltage.

(vi) Each cycle of the ignition oscillations lasts for about 10 microsec and may be repeated some 10 to 50 times before the Al-arc is finally formed, which then burns steadily, without further appreciable voltage change, to the end of the reverse polarity half-cycle.

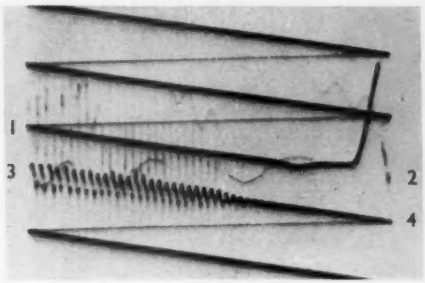
The general appearance of these oscillations suggests a tungsten-aluminium argonarc at a much higher frequency than the 50 c/s power arc, viz., of the order of 100,000 c/s,



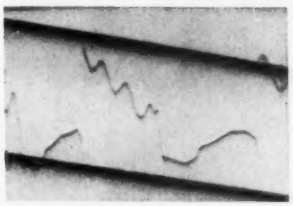
(*a*) (see sketch Fig. 16a.)



(*b*) (See sketch Fig. 16b.)

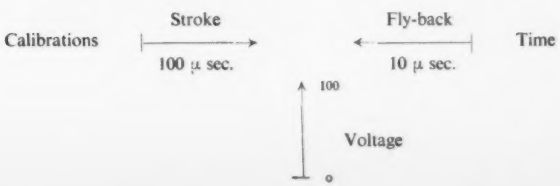


(*c*)



(*d*) Detail of ignition oscillation resolved on fly-back (Time ←).

Fig. 15.—High-speed oscillograms of self re-ignition type E.
(*See Section* 6.1.)



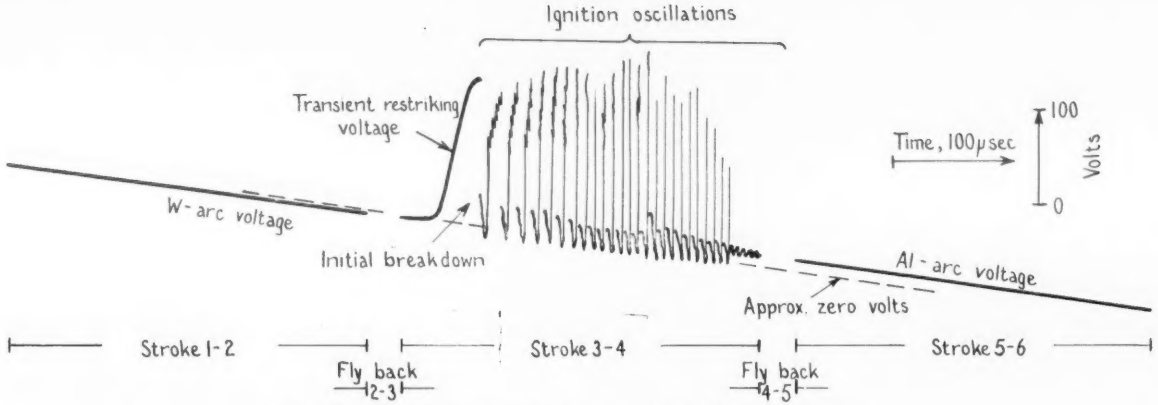


Fig. 16(a).—Sketch of H.S. oscillogram Fig 15(a) of self re-ignition type E.

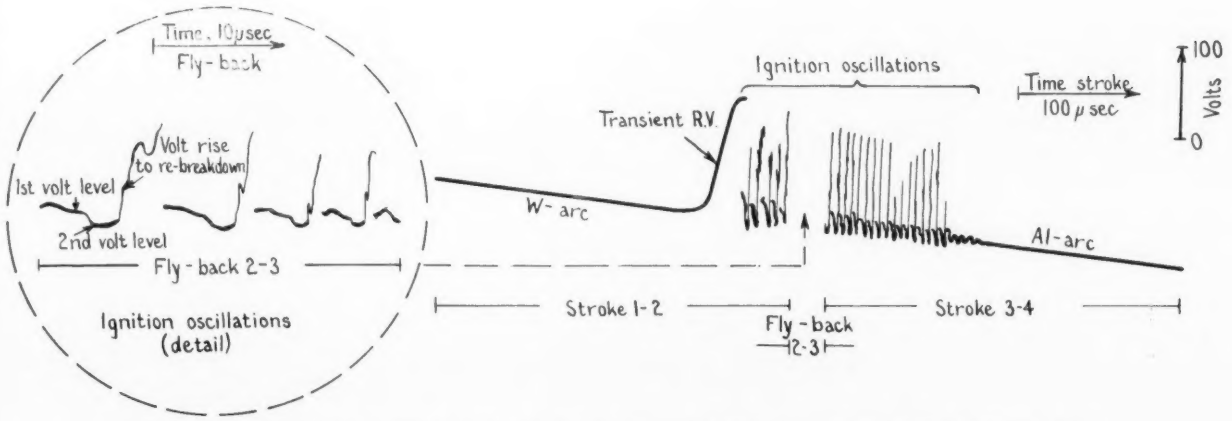


Fig. 16(b).—Sketch of H.S. oscillogram Fig. 15(b) of self re-ignition type E (showing details of ignition oscillations on fly-back).

with similar high voltages required to re-start the arc for W to Al transition only.

A probable explanation of these ignition oscillations is that the sudden collapse of voltage across the gap at breakdown causes a local oscillatory current to flow, owing to the residual capacitance and inductance associated with the circuit to the arc. This current initially forms an Al-arc, which then changes into a W-arc, and, at the end of the small W-loop of the oscillatory current, the arc extinguishes as in the case of the power arc, and the voltage across the gap then builds up again to the next breakdown. (The ripple in the Al-arc voltage at the end of the re-ignition period indicates an oscillatory current of about 150 kc/s).

6.2. Delayed Self Re-Ignition (Soft Gap Breakdown)

For a self-running arc the oscillograms show that an alternative type of self re-ignition to that discussed above can exist. This alternative is the formation of a " soft gap," as an intermediate stage prior to the ignition oscillations, for which the gap " resistance " assumes a value between that of the open-circuit and arc states. The soft gap modifies the restriking voltage (compared with the inherent R.V.), and possibly also the arc re-ignition process. This delayed self-ignition is especially apparent for the scratch-brushed Al-5% Mg alloy (see Fig. 6).

With increase in the open-circuit voltage the onset of softening of the gap at the start of the Al-h.c. modifies or damps the oscillation of the transient R.V., as may be seen by comparing the high-speed oscillograms of the restriking voltages for soft gaps in Figs. 18 (a), (b), (c) with that for a half-cycle rectification in Fig. 17.

Increasingly soft gaps cause a distinct drop in the gap restriking voltage following W-arc extinction, compared with that for a rectifying arc (e.g., see Fig. 5 (a)). This voltage difference is also well illustrated by the sketch in Fig. 19 which superimposes the high-speed oscillograms of Figs. 17 and 18 (a).

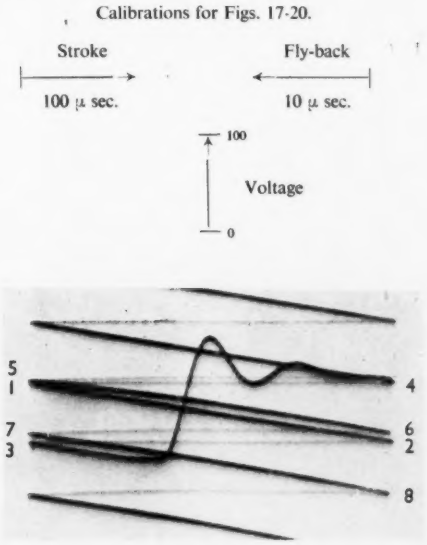


Fig. 17.—H.S. oscillogram of a rectification showing transient restriking voltage.
(*See Sketch Fig.* 16.)

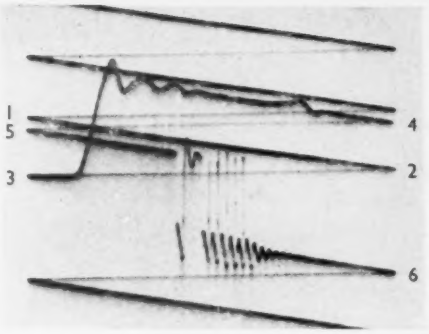


Fig. 18(a)
(*See Sketch Fig.* 19.)

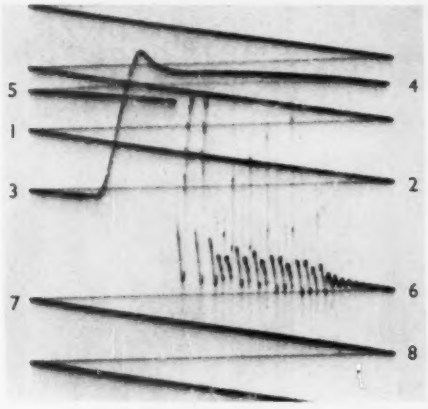


Fig. 18(b).

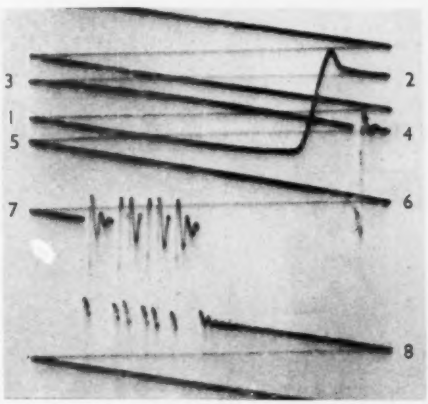


Fig. 18(c).

Fig. 18.—H.S. oscillograms of delayed self re-ignition type D—soft gap. (*See Section* 6.2.)

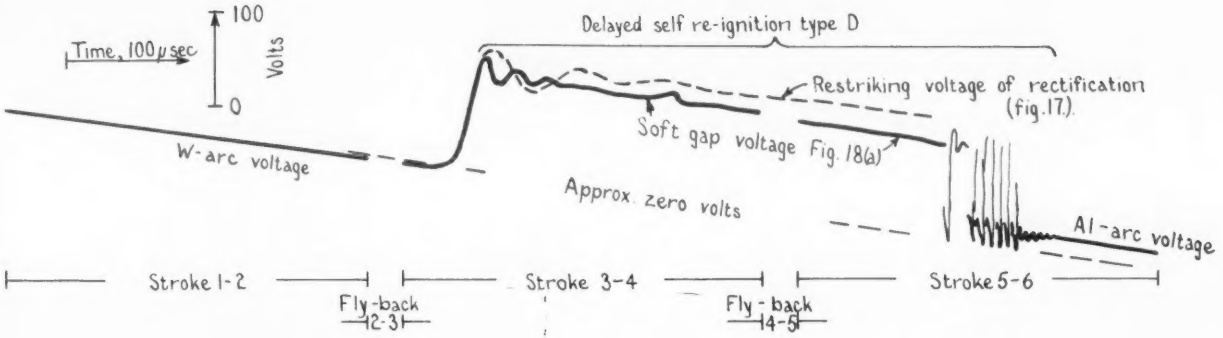
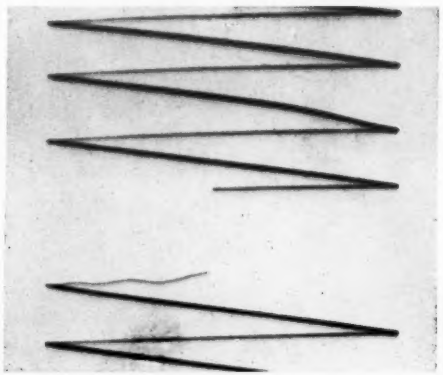


Fig. 19.—Sketch of H.S. oscillograms Figs. 18(a) and 17 showing change in restriking voltage for soft gap.



(*left*) **Fig. 20.**—Final ignition stage of delayed self re-ignition type D for a very soft gap (no ignition oscillations).

The soft gaps can suddenly break down and lead to the Al-arc with a similar oscillatory ignition period as for self re-ignition, Section 6.1 above, but with in general fewer oscillatory cycles (Figs. 18 (a) and (b)), and, for the softer gaps, with some modification in the appearance of the ignition oscillations such as shown in Fig. 18 (c). In the extreme, where the gap voltage is held much lower than the open-circuit voltage for an appreciable part of a millisecond, the ignition oscillations do not occur. For example, in the first two cycles, Fig. 3 (a), the very soft gap breaks down to an Al-arc, which then burns steadily throughout the half-cycle. The fly-back of the high-speed oscillogram, Fig. 20, shows the final breakdown from a soft gap occurring in not more than about 10^{-7} sec.

It seems that in these very soft gap breakdowns the conduction in the gap has become so great that the maximum negative value of the local oscillatory current after breakdown is insufficient to reverse the arc polarity, even momentarily.

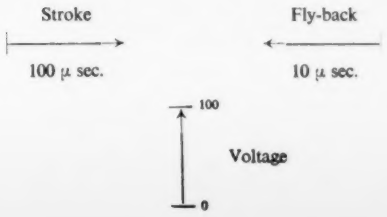
6.3. Spark Re-Ignition

Re-ignition of the arc on the reverse polarity half-cycle by high-frequency sparks is very similar to the oscillatory self re-ignition discussed above. The main difference is that the restriking voltage itself is not high enough to break down the gap, and so the arc rectifies. The injection of a high-voltage h.f. spark serves to break down the gap *initially*, and thereafter the ignition oscillations take place as above. The Al-arc then conducts for the remainder of the half-cycle as for partial rectification.

These ignition oscillations here had an overall duration of the order of $0{\cdot}2 \times 10^{-3}$ sec., whereas the duration of the h.f. spark is about 10^{-6} sec., and the interval between sparks 10^{-3} sec. (See, for example, the high-speed oscillogram, Fig. 21, of the voltage across the arc with superposed h.f. injection which just resolves the sparks on the stroke, and more clearly on the fly-back of the time base—showing an oscillation of about 2 Mc./sec., and an average logarithmic decrement of 0·6, i.e., linear ratio of amplitudes of about 50 per cent.). This point is emphasised to dispel a belief that the high frequency oscillations from the spark injector have not died out before the next spark generates a fresh train. The oscillatory bands at the re-ignition of the Al-arc, shown on the slower speed cathode ray oscillograms, are not the h.f. sparks but the ignition oscillations, which last some 10 times to 100 times longer.

The high-speed records, Figs. 22 (a) and (b), of the spark re-ignition of the Al-arc show that the magnitudes of the fast transient voltages of the oscillatory breakdowns are similar to those for self re-ignition. Thus even when the inherent restriking voltage is low (Fig. 22 (b)), the transient voltages generated by the arc and the circuit together (once the h.f. spark has brought about the first breakdown of the gap) are greater than the normal gap voltage for a rectifying arc.

Calibrations for Figs. 21-23.



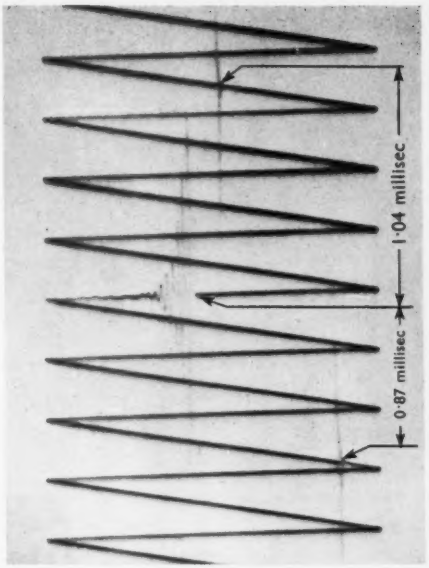


Fig. 21.—H.S. oscillogram of spark injection across arc.

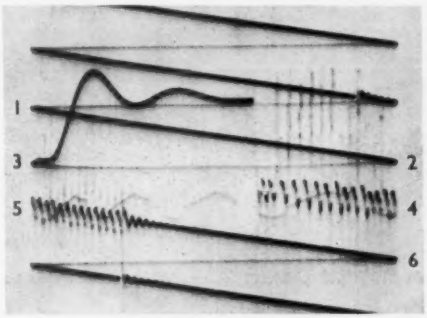


Fig. 22(a).—High open circuit voltage.

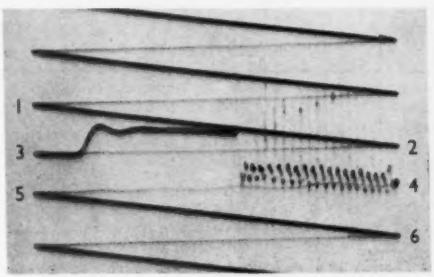


Fig. 22(b).—Low open circuit voltage
(*See Fig. 2c.*)

Fig. 22.—H.S. oscillograms of spark re-ignition of arc.
(*See Section* 6.3.)

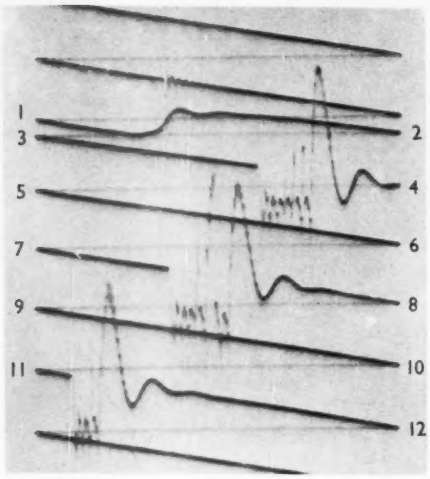


Fig. 23.—H.S. oscillogram of spark breakdown of gap with failure of ignition oscillations

(*See Fig. 2a and Section 6.3.*)

At still lower open-circuit voltages of the welding transformer, more than one h.f. spark is required for re-ignition (or even complete rectification may occur in spite of the spark injection), see Section 4.2. It is not a case of the spark failing to break down the gap initially, but that the subsequent transient voltage-rises which are generated in the circuit are not sufficiently high or fast to cause further breakdowns leading to the establishment of the Al-arc proper. Fig. 23 shows the high-voltage surge that is generated by the ignition processes when the gap fails to break down again. The decay of these high voltages at a similar frequency to the transient R.V. oscillation should be noted.

7. DISCUSSION

7.1. Critical and Minimum Satisfactory Open-Circuit Voltage

The data in Figs. 6 and 7 and Table 1 show that the 100-volt r.m.s. leakage-reactance type transformer, with no series capacitor, could not maintain a self-running arc, the minimum open-circuit voltages to avoid possible intermittent rectification being 125 volts r.m.s. for the Al-5% Mg alloy, and 160 volts r.m.s. for commercially pure aluminium. Thus some form of auxiliary arc re-ignition, such as the injection of h.f. sparks, is necessary. Having admitted spark injection, then a considerable reduction in open-circuit voltage is possible. A 100-volt r.m.s. leakage-reactance transformer in conjunction with well-phased h.f. sparks is seen from Table 1 to be fully adequate for argonarc welding of aluminium, and for particular materials much lower voltages are satisfactory, e.g., down to 60 volts for the degreased alloy with 45 volts as a lower limit in these tests.

The differences in open-circuit voltages given in Tables 1 and 2 for the different plate materials tested under otherwise

TABLE 1

Work Plate Material and Surface Treatment	1	2	3	4
	Open-Circuit Voltages for Arc Re-ignition: No Series Capacitor			
	By H.F. Sparks		Self Re-ignition	
	Critical	Minimum Satisfactory	Critical	Minimum Satisfactory
Al-5% Mg degreased	45	60	105	125
Al-5% Mg scratch-brushed	60	85	115	125
Al (2L4) scratch-brushed	85	95	150	160

TABLE 2

Work Plate Material and Surface Treatment	1	2	3	4
	Open-Circuit Voltages for Arc Re-ignition: Using Large Series Capacitor			
	By H.F. Sparks		Self Re-ignition	
	Critical	Minimum Satisfactory	Critical	Minimum Satisfactory
Al-5% Mg degreased	< 45 ?	45	95	105
Al-5% Mg scratch-brushed	45	60	105	115
Al (2L4) scratch-brushed	> 60 < 85	85	125	140

the same conditions are sufficiently great to be significant. The materials in order of increasing voltage are—Al-5% Mg degreased, Al-5% Mg scratch-brushed, and Al (2L4) scratch-brushed, the voltage differences being approximately 15 volts between the first pair, and 25 volts between the last pair.

The addition of a large series capacitor results in a general lowering of the open-circuit voltage for all test conditions, and from Tables 1 and 2 the average drop is seen to be about 15 volts (see Section 7.2). It is interesting to note that with h.f. spark injection it should be possible to argonarc weld degreased Al-5% Mg at even less than 45 volts r.m.s. which was the lowest voltage obtainable in these tests.

Figs. 6 and 7 indicate that the insertion of a series capacitor, giving an equivalent open-circuit voltage increase of about 15 volts, would not cause such marked change in the arcing behaviour as is sometimes claimed, except of course when the voltage before insertion was near critical (for the avoidance of rectification when using h.f. injection or for self re-ignition without h.f.). If however, the h.f. is badly phased and the voltage near critical for self re-ignition, then, as already stated in Section 4.3, the series capacitor can markedly improve the appearance of a melt run (see Figs. 9 (a) and (b)). For Fig. 9 (a) before capacitor insertion about 50 per cent. of the cycles self re-ignited, the remainder being late spark breakdowns, and after capacitor insertion, the arc was mainly self re-igniting. Fig. 9 (b) shows a very marked change from mainly rectifying, since h.f. was injected very late in the half-cycle, to late spark re-ignition and self-breakdown occurring in about equal proportions.

Comparison of Columns 1 and 2 with 3 and 4 in both Tables 1 and 2 shows that the injection of h.f. sparks permits about 60 volts drop in the open-circuit voltage. But where radio interference is too severe to allow continual h.f. injection, then with the higher transformer voltages, such as those for critical self re-ignition, a high-speed relay might be used to operate the injector for a short time should an arc outage occur. Such a system, although not affecting the interference level, would reduce the nuisance value.

As previously emphasized, the low open-circuit voltages established with permanent h.f. injection depend on the sparks being well phased. For example, the melt run at 105 volts on commercially pure Al, Fig. 8 (d), is far more satisfactory than the run also at 105 volts (left hand section of Fig. 9 (b)), where the h.f. injection is so late that rectification occurred for most of the reverse polarity half-cycles. If the sparks are incorrectly phased then satisfactory welding would probably not be achieved until the open-circuit voltage was raised to where the arc became substantially self re-igniting.

The range of open-circuit voltages for a self-running arc (Column 4, Table 1) is similar to that mentioned by Wassell[3]. In this present work it is entirely due to changes in work plate material, all other parameters being constant. Such a range of voltage may account for the seemingly high values of 200 volts r.m.s. and 240 volts r.m.s. to avoid rectification given by Welch[5] and by Sillifant and Woollcott[6] respectively, which were probably quoted high to allow for different working conditions. For a given arrangement, however, the critical and minimum satisfactory open-circuit voltages can be established within fairly narrow limits. The tables show, however, that there is a danger in over-generalizing on values of open-circuit voltage for argonarc welding and if the voltages are near critical then the test conditions should be clearly defined. From general arc considerations the critical open-circuit voltage is likely to be affected by parameters such as rate of argon flow, traverse rate, gap setting, current, etc. Within reasonable limits such factors probably do not have such a major influence as do types of circuit, work plate material, etc. With a more refined test technique the effects of the less important parameters on arc re-ignition could be determined.

Working under optimum conditions from both the welding and the arc re-ignition aspects will to some extent lower the figures given in the tables, but the general effects of the various parameters will probably remain unaffected. The tables do also demonstrate that, under many conditions, leaky-reactance type transformers of quite low open-circuit voltage, designed possibly for ferrous welding, can be used for aluminium welding by the argonarc process.

7.2. Arc Re-Ignition

In the sections dealing with arc re-ignition, the physical arc processes at the cathode, the anode, and in the column have not been studied as such. The oscillograms, however, show the voltages resultant from these processes and can be used to explain the open-circuit voltage figures for arc maintenance under different conditions, quoted in Tables 1 and 2.

An essential factor is the voltage required, following the extinction of a W-arc, to break down the gap for any given plate material, surface preparation, etc. The fact that under otherwise identical test conditions, commercially pure aluminium requires higher transient voltages for breakdown than, for instance, an Al-5% Mg alloy, necessitates for the former higher open-circuit voltage settings of the welding transformer. As shown above, however, if well-phased h.f. sparks are used to break down the gap instead of depending on self-breakdown, then a major drop in open-circuit voltage can be made, down to a value which here marked the limit of the circuit to provide adequate transient voltages for the oscillatory ignition of the arc (Column 1 of Tables 1 and 2). It should be noted that badly-phased sparks, injected late in a half-cycle, when the available open-circuit voltage has fallen, may similarly fail to re-ignite the arc in spite of a nominally higher open-circuit voltage. Since the h.f. spark serves only to break down the gap initially but does not complete the re-ignition processes, greater h.f. power is not likely to be of value and will only increase the already severe radio interference. Thus the voltages quoted for spark maintenance of the argon-arc in Columns 1 and 2 of the tables will not be appreciably lowered by such steps.

Finally, the addition of h.f. injection does not primarily "stabilize" the Al-arc, for if the Al-arc is once established in any one half-cycle it continues to burn to the end of that half-cycle, whether h.f. sparks are present during this period or not. However, if at lower open-circuit voltages sparks are used to break down the gap, subsequently leading to arc formation, no further sparks are required for that half-cycle. This explains how an h.f. spark oscillator of only a few watts mean power can "stabilize" (so-called) an argonarc of the order of a kilowatt in power.

In the a.c. argonarc more current flows in the half-cycle in which the tungsten rod is the cathode. Thus there is a mean excess of current (the d.c. component) which is equivalent to a flow of electrons from the tungsten. When a large series capacitor is inserted between the transformer and the torch, the excess flow of electrons leaves the capacitor plate on the torch side positively charged. Thus in the reverse polarity half-cycle, rod positive, the effective voltage is the transformer open-circuit plus the capacitor charge. In practice, eliminating the mean d.c. component by inserting a series capacitor produces a positive charge of about 10 to 20 volts which accounts for the general drop of 15 volts in the required open-circuit voltages as between corresponding tests in Tables 1 and 2. The oscillogram of Fig. 14 shows on the lower and upper strips respectively the effective open-circuit voltage before and after insertion of a series capacitor.

8. CONCLUSIONS

1. The cathode ray oscillographic analysis has revealed the complex nature of arc re-ignition in the argonarc process, and the bearing of open-circuit voltage on arc re-ignition characteristics.

2. The electrical characteristics are markedly different for the straight polarity (W-arc) and reverse polarity (Al-arc) half-cycles. The arc voltage is lower for the W-arc than for the Al-arc, and has a positive as against a substantially flat characteristic.

3. The W-arc re-ignites at a very low voltage as soon as the potential across the gap becomes negative, and falls to a similar low value towards the end of the half-cycle. On the other hand the re-ignition of the Al-arc requires a positive voltage of the order of 100 volts for gap breakdown, and at the end of the half-cycle the gap voltage often rapidly rises before abruptly falling to zero.

4. If the reverse polarity half-cycle rectifies, then the re-ignition voltage of the W-arc increases very rapidly with increasing gap length, and to avoid total arc outage, in the absence of h.f. injection, it was found that the gap length had to be less than about $\frac{1}{8}$".

5. The re-ignition characteristics of the Al-arc can be complex. In a typical welding circuit the gap initially broke down to voltages similar to the Al- and W-arcs followed by a rapid transient rise to a voltage sufficient to cause re-breakdown. This cycle of events took about 10 microseconds, and may be repeated some 10 to 50 times, before the Al-arc proper is finally established.

These ignition oscillations can occur whether initial gap breakdown is caused by an injected spark or by a sufficiently high open-circuit voltage for the arc to be self-maintaining.

6. At low open-circuit voltages where h.f. spark injection serves to break down the gap and ignition oscillations are initiated, then unless the open-circuit voltage is adequate to maintain the subsequent oscillations, the Al-arc will not be established.

7. In a self-maintaining arc, under certain conditions, following the extinction of the W-arc, re-ignition of the Al-arc is delayed for an appreciable part of a millisecond, during which time the gap is "soft," i.e., it has a resistance between the open-circuit and arc states. This soft gap modifies the circuit restriking voltage and sometimes the ignition oscillations themselves.

8. With h.f. injection, there are three types of Al-arc re-ignition : (*A*) failure to re-ignite, i.e., complete rectification ; (*B*) more than one spark required for re-ignition ; (*C*) one spark only for re-ignition. For a self-maintaining arc two types of Al-arc re-ignition have been recognized ; (*D*) delayed self re-ignition (soft gap) ; (*E*) immediate self re-ignition.

9. The introduction of h.f. spark injection lowers by about 60 volts the " minimum satisfactory " and " crucial " open-circuit voltages for arc maintenance. This is because the h.f. spark can break down the gap, where the circuit voltage itself could not, a lower limit to open-circuit voltage being set here by failure of the Al-arc ignition oscillations.

10. The main function of h.f. spark injection being to break down the gap initially explains how a spark oscillator with a mean power output of a few watts can " stabilize " an argonarc of the order of a kilowatt in power.

11. The work plate material, and its surface state, have a marked effect on the critical and minimum satisfactory open-circuit voltages, under all the conditions of test (e.g., degreased to scratch-brushed Al-5% Mg. alloy, and Al-5% Mg alloy to Al (2L4) both scratch-brushed, approximately 15 volts and 25 volts increase respectively).

12. The insertion of a large series capacitor in the welding circuit lowered the critical and minimum satisfactory open-circuit voltages by about 15 volts. This is because the charge acquired by the capacitor in countering the d.c. component adds to the open-circuit voltage for re-ignition of the Al-arc.

13. Addition of a capacitor only causes a marked improvement in arcing behaviour when the open-circuit voltage is near critical and particularly in the case of badly phased h.f. injection.

14. For any given experimental set-up a definite minimum satisfactory open-circuit voltage can be established. The differences in open-circuit voltages found here for the various test arrangements provide a probable explanation for the divergence in values quoted in literature.

15. Without auxiliary means for arc re-ignition, such as h.f. spark injection, the 100-volt r.m.s. leaky-reactance type transformer is unsuitable for argonarc welding aluminium (2L4) or Al-5% Mg alloy, since the minimum satisfactory open-circuit voltages are about 160 volts r.m.s. and 125 volts r.m.s. respectively. It should be noted, however, that, using the above type transformer, designed possibly for ferrous welding, with well-phased h.f. spark injection and a series capacitor, the argonarc can be successfully run at an open-circuit voltage as low as 45 volts r.m.s., on a degreased Al-5% Mg alloy work plate.

Acknowledgments

Thanks are expressed to Mr. J. H. Cole of the British Welding Research Association for his assistance, and to Mr. P. Lale for help in the experimental work.

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R.75

SPOT WELDING OF COATED MILD STEEL SHEET

The experimental work described in this report is a combination of several ad-hoc investigations on the spot welding of mild steel sheet protected by electro-deposited coatings of cadmium and zinc. These investigations were conducted by the Liaison and Development Department of B.W.R.A. in order to provide operational data at the request of certain member firms who had experienced production difficulties.

By A. J. HIPPERSON, B.Sc. (Eng.) and P. M. TEANBY

INTRODUCTION

It has been found in practice that certain metallic coatings on mild steel sheet tend to affect the ease with which spot welds of high strength and quality may be made. It was the object of the work to determine to what extent resistance welding can be applied to the fabrication of cadmium and zinc-coated sheet steel assemblies in production.

The types of deposit investigated were cadmium 0·0003 in. thick, zinc 0·0001 in. thick and phosphated zinc 0·0001 in. thick. Control tests were made on uncoated sheet of the same gauge for comparative purposes.

SCOPE OF INVESTIGATION

Object

The object of the investigation was to determine the applicability of spot welding to the fabrication of coated steel sheet assemblies in production, with particular reference to the modification in technique required compared with the welding of uncoated sheet, and the nunber of satisfactory welds which can be made without special attention to electrodes.

Material

The parent metal used in all tests was low carbon, deep drawing quality mild steel, 16 s.w.g. thick.

Electrode Materials

Electrodes manufactured from hard drawn chromium copper were used exclusively throughout the work. Its approximate properties were:

Vickers hardness 150.
Conductivity of I.A.C.S. 80 per cent.
Softening Temperature 500 deg. C.

Mechanical Tests

Tensile tests on welded samples were carried out using a mechanically operated tensile testing machine. The tests were supplemented with manual torsion tests which are more indicative of weld nugget diameter than tensile tests.

Spot Welding Machine

The machine used for all the spot welding tests was a fully automatic air-operated machine manufactured by Metropolitan-Vickers Ltd., and rated at 25 kVA. The maximum open circuit secondary voltage was 3·5, and at this tapping the current was 8,680 amps., these readings being obtained with a throat depth of 22½ ins. and a throat gap of 13 ins.

The mains voltage supply to the primary was 430 volts. The primary current was controlled by a single pole electromagnetic contactor and the weld duration by a resistance capacity timer.

The magnitude of the welding current was selected by the transformer primary tapping. Five tappings were available giving open circuit secondary voltages ranging from 1·54 to 3·5 volts. (See Table I.)

Electrode pressure could be adjusted by means of a reducing valve in the air supply to the cylinder of the machine head. (See Table II.)

The short circuit secondary current and welding time were measured by means of a cathode ray oscilloscope and recorded on paper film.

The spot welding electrodes were all machined from ¾ in. diameter stock, and their shanks had an included angle of 5 deg. in accordance with B.S. 807. Each electrode had a water cooling hole extending to within ½ in. of the electrode tip. Where truncated cone type of electrodes were used the included angle was 120 deg., and the initial diameter of the flat surface was 3/16 in.

PRELIMINARY SPOT WELDING TESTS

Water cooling was supplied to both spot welding electrodes by a series arrangement, and the rate of flow of water was maintained at 1 gallon per minute, minimum.

Most of the endurance tests were made at a rate of welding of 40 welds per minute, not including the test welds for macrophotography, tensile testing, etc.

Preliminary tests were made on 16 s.w.g. uncoated sheet, using various machine settings. The nominal diameter of the electrode tips was 3/16 in. The values of secondary current

and electrode force which produced the most satisfactory results were 7,443 amps. and 275 lbs. The welding time, i.e. the duration of current flow, was 18 cycles.

For welding all the coatings under examination the best settings were found to be 8,350 amps. and 415 lbs., with the duration of current flow remaining at 18 cycles. It was found that a higher current density was required to maintain weld size and additional pressure to neutralise the tendency for expulsion of molten metal.

The welding results were apparently satisfactory as indicated by the torsion test and as a higher transformer tapping resulted in considerable intersheet splashing the above values were decided upon as those to use for the electrode endurance tests.

MAIN SPOT WELDING TESTS

The main spot welding tests were conducted in the following manner:

Three single spot specimens were made, one for tensile, one for torsion testing and one for subsequent examination.

Fifty welds were then made at a constant rate at a pitch of about ½ in. on flat sheet, after which another set of specimens were made similar to the first ones.

This was repeated up to the following number of welds.

Zinc plated	500 welds
Phosphated zinc plated	500 ,,
Cadmium plated	200 ,,
Passivated cadmium plated ..	500 ,,

making a series of test welds every 50 or 100 welds. Unfortunately, due to lack of material, the tests on cadmium plated material had to be terminated at the 200th weld.

TESTING OF SPOT WELDS

The single spot specimens made during the tests were pulled to destruction in a mechanically operated tensile testing machine.

The specimens consisted of two pieces of strip 1½ ins. wide and 6 ins. long. The test pieces were overlapped for a distance of 1½ ins. and joined at the centre of the overlapping area by a single spot weld approximately 7/32 in. diameter. For each specimen tested, the maximum load was recorded and also the method of failure, i.e. whether of the "shear" or "tear" type.

A further mechanical test for the spot welds was used in order that a quick and approximate guide as to their strength and quality could be obtained whilst welding tests were proceeding. These consisted of overlapping two strips 1½ ins. by 4 ins. at right angles, and spot welding in the centre of the overlapping area. The specimens were subjected manually to torsion, thereby subjecting the weld interface to torsional shear. It was considered that the quality of welding could be judged approximately by the visual appearance of the fractured surface.

Selected spot welds were sectioned across a diameter and polished and etched for microscopical examination. It was noted that slight porosity was present in nearly all the welds. At the same time the fused area was regular and of good dimensions.

DISCUSSION OF TESTS AND RESULTS

Previous work on tin and tin zinc coatings has indicated the superiority of chromium copper as an electrode tip material for production work due to the slow rate of mushrooming of the tips, and consequently the longer electrode life.

A disadvantage of chromium copper when used on tin coatings is the greater tendency to sticking compared with pure copper or cadmium copper, but this is more than offset by the former consideration. In the present tests, little or no sticking occurred when adequate water cooling was used, so that the question of using electrode materials other than chromium copper was not investigated.

Table I.—Machine Characteristics

Transformer Tap	Short Circuit Sec. Current (amps.)	Open Circuit Sec. Voltage (volts)
1	4,960	1·54
2	6,200	2·06
3	7,440	2·51
4	8,350	3·00
5	8,680	3·50

Table II.—Pressure Calibration

Pressure on Gauge	Actual Force in lbs.
25	110
35	180
50	310
75	500
93	645

In accordance with the formula $D = \sqrt{t}$, ¼ in. diameter electrode tips are normally used for welding 16 s.w.g. sheet, but due to the fact that space is often restricted on the components normally manufactured from the materials in question, 3/16 in. diameter electrode tips were used throughout the present tests. It was found that good welds could be produced with this electrode tip size, provided the other welding variables were suitably selected.

The series of tests which were conducted on cadmium plated sheet without water cooling resulted in an extremely short electrode life, and showed the desirability of adequate water cooling for this type of work.

WELDING VARIABLES

Control tests were first made using uncoated sheet. The variables which were kept constant in these tests were electrode pressure, tip size and welding time, as follows:

Electrode pressure ..	10,000 lbs. per sq.in. (275 lbs.)
Tip diameter	3/16 in.
Welding time	18 cycles

Welds were made using various transformer tappings to determine the range of current which gave satisfactory results. Results were judged by the torsion test and provided a cast nugget 3/16 in. in diameter or more was obtained, the results were considered satisfactory.

The following summarised results were obtained:

At 4,962 amps.	No fusion
,, 6,202 amps.	3/16 in. dia. weld
,, 7,443 amps.	7/32 in. dia. weld
,, 8,350 amps.	7/32 in. dia. weld, severe splashing
,, 8,683 amps.	Excessive splashing

It would, therefore, appear that the range of current giving good welding conditions for uncoated sheet is approximately 6,200 amps. to 7,450 amps.

The zinc plated sheet was the first to be examined. The tests indicated an optimum welding current between tap 3 and tap 4 (7,443 amps. and 8,350 amps.), splashing being obtained on tap 4. To eliminate this splashing, the pressure was increased to 15,000 lbs. per sq. in. (410 lbs.) and was maintained at this figure for all subsequent tests on the three other coatings under test.

Using this pressure and a welding time of 18 cycles, in general the following approximate results were obtained:

At 6,202 amps.	No fusion
,, 7,443 amps.	⅛ in. dia. weld
,, 8,350 amps.	7/32 in. dia. weld.
,, 8,683 amps.	Excessive splashing

The results are tabulated in Table III.

Table III

Transformer Tap	Welding Current in Amps.	Plain Sheet. Electrode Pressure 275 lbs.	Zinc Plated Sheet. Electrode Pressure 275-410 lbs.	Phosphated Zinc. Electrode Pressure 410 lbs.	Cadmium Plated. Electrode Pressure 410 lbs.	Passivated Cadmium. Electrode Pressure 410 lbs.
1	4,960	No fusion	No fusion	No fusion	No fusion	No fusion
2	6,200	3/16 in. diameter weld	No fusion	No fusion	No fusion	No fusion
3	7,440	7/32 in. diameter weld	1/8 in. diameter weld	3/16 in. diameter weld	1/8 in. diameter weld	3/32 in. diameter weld
4	8,350	7/32 in. diameter weld with moderate splashing	1/4 in. diameter weld slight splashing. Pressure increased to 15,000 lbs. per sq.in. (410 lbs.)	7/32 in. diameter weld	7/32 in. diameter weld	3/16 in. diameter weld
5	8,680	Excessive splashing	1/4 in. diameter weld Excessive splashing	Excessive splashing	Excessive splashing	1/4 in. diameter weld Excessive splashing

From the table, it is clear that the value of current required for welding plated sheet is more critical than that for plain sheet.

Electrode pressure does not appear to be critical in the range examined, so far as is indicated by the foregoing tests. 15,000 lbs. per sq. in. tends to decrease the tendency to splashing as compared with 10,000 lbs. per sq. in., and does give a bigger safety margin in practice, particularly where some of the applied load is absorbed in bringing the components together, a condition which is often met when two stiff pressings or sections are to be joined.

Generally speaking, all the tests were carried out in such a way as to attempt to keep in the 10,000-15,000 lbs. per sq. in. pressure range, using a welding time of 18 cycles, and selecting the transformer tappings to give satisfactory results. When that transformer tapping giving a current most closely approaching the optimum tended to give rise to splashing, the pressure was adjusted so that it was high in the range stated. Where the current was slightly low, an increase in welding time was effected to secure optimum results.

The rate of flow of cooling water was kept constant at 1 gallon per minute in all main tests, and no electrode sticking was apparent, except in the case of zinc coated sheet after about the 200th weld.

ENDURANCE TESTS

Spot welds in all the materials, showed no marked decrease in weld strength or size up to 500 welds at which point the tests were terminated.

In the case of cadmium plated sheet, the tests were terminated at the 200th weld due to lack of material. It is reasonable to assume that many more welds could have been made without serious deterioration of weld quality, since the electrode tips were not appreciably affected. Fig. 1 illustrates the particular results of each coating, weld strength being plotted against number of welds.

MACRO-EXAMINATION

Sections of welds made at the end of each series were examined and macrophotographs are shown in Figs. 2 to 8 inclusive. It will be seen that in all cases, even at the end of the endurance tests, satisfactory cast weld nuggets were obtained. In the case of the phosphated zinc coated sheet, three small unwelded areas were visible, but it is considered that they were of insufficient size appreciably to affect the strength of the weld.

CONCLUSIONS

There are two distinct effects which adversely affect the spot welding of coated mild steel sheet, viz. electrode sticking and sensitivity of spot weld size and quality to small changes of machine settings, such as line voltage fluctuations and increase in electrode tip size.

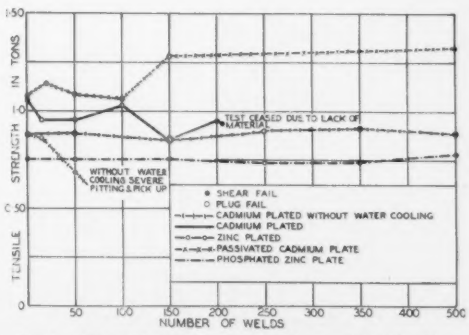

Fig. 1. Spot weld strength plotted against number of welds.

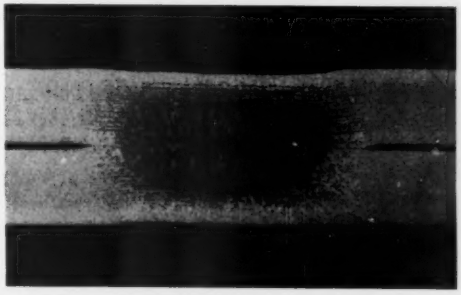

Fig. 2. Uncoated sheet. Mag. ×8 (approx.)

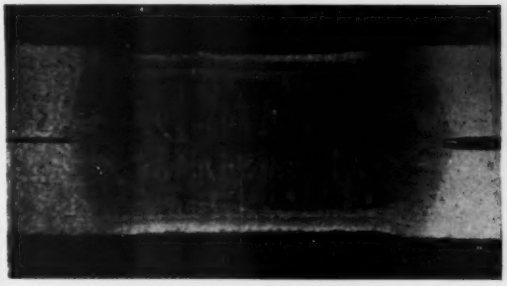

Fig. 3. 200th weld in cadmium plated sheet. Mag. ×8 (approx.)

The conclusions drawn from the spot welding tests are summarised below:

(*a*) Acceptable welds were produced in all cases apart from phosphated zinc which gave less sound welds.

(*b*) Provided that adequate water cooling is available, little or no sticking between the electrodes and workpiece was obtained.

(*c*) Using chromium copper electrodes a useful electrode life of over 500 welds can be expected.

(*d*) Weld strength maintains a satisfactory figure up to 500 welds, which was the limit of the present tests.

(*e*) Spot welding these materials is quite practicable under production conditions, provided the limitations as to electrode life are adequately catered for and machine settings are carefully controlled.

RECOMMENDATIONS

Arising from this work, and previously published information,[1] it is possible to make the following recommendations for spot welding cadmium plated mild steel sheet:

(*a*) In order to minimise the increase in electrode tip size, which occurs in production, an electrode material should be used which possesses good conductivity and mechanical properties at elevated temperatures, such as chromium copper. A short stroke should also be used, so as to minimise deformation due to impact.

(*b*) As high a welding current as possible should be used, consistent with freedom of expulsion of molten metal from the weld zone.

(*c*) Efficient internal cooling of electrodes should be provided so as to minimise electrode sticking and electrode deformation.

(*d*) An electrode tip pressure in the range 10,000 to 15,000 lbs. per sq. in. should be used. The duration of welding current should be about 18 cycles for welding coated sheet, 16 s.w.g. in thickness,

(*e*) Before a machine setting is used in production, simple manual torsion tests or other destructive tests should be carried out on strips of the actual material to be welded, to ensure that a weld nugget is being produced which is capable of withstanding failure through the original interface.

Reference

1. Hipperson, A. J., and Teanby, P. M. "An Evaluation of the Resistance Welding of Tin and Tin-Zinc Alloy Coated Mild Steel Sheet," *Welding Research*, vol. 3, No. 5 (Oct. 1949).

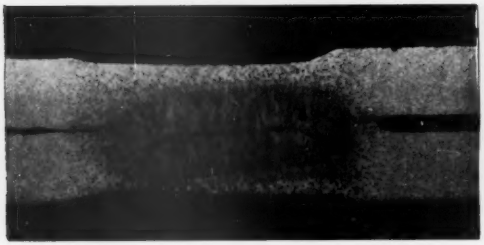

Fig. 4. Phosphated Zinc coated sheet. Mag. ×5 (approx.)

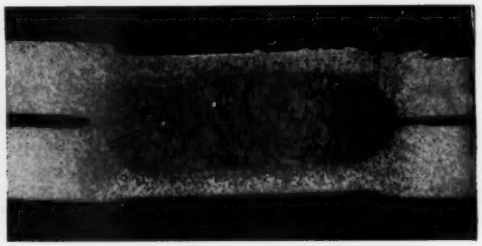

Fig. 5. Zinc coated sheet. Mag. ×5 (approx.)

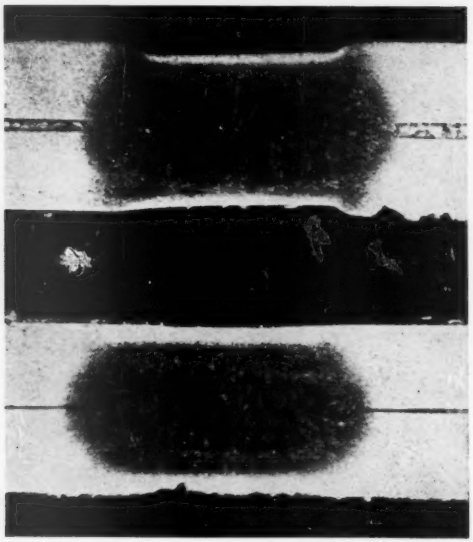

Fig. 6. (left) 1st weld in passivated cadmium plated sheet. Mag. ×5 (approx.)

Fig. 7. (left) 500th weld in passivated cadmium plated sheet. Mag. ×5 (approx.)

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